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POLICY BRIDGE

The complex Andes region needs improved efforts to face climate extremes

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The steep slopes, highlands, and valleys of the Andes mountain chain are inhabited throughout its formidable length. This unique characteristic does not repeat in any other mountain region. The Andes shape weather and climate in South America. However, proper understanding of atmospheric phenomena influenced by a daunting altitudinal gradient is still behind what is needed to produce detailed and consistent climate projections. Despite significant advances, global models misrepresent key precipitation and circulation processes that are influenced by complex topography. Along with a lack of coordinated observations, the result is limited information to design preparedness measures, particularly to face extreme climate events. Of equal concern is the issue of air quality in densely urbanized countries that face decarbonization challenges and share a legacy of social inequity and political unrest. The complexity of the Andes region magnifies risks within all nations that share their influence. Thus, urgent action is needed to improve climate and air quality assessments with the direct purpose of strengthening policy-making processes.

Keywords: Andes, South America, Climate change, Climate policy, Climate extremes

1. A need for a dedicated focus on climate research

The Andes is the longest mountain chain in the world. Atmospheric circulation over 7,000 km of Andean length extends from the Intertropical Convergence Zone (ITCZ), that seasonally hovers north and south of the equator, to the subpolar circulation over Patagonia. Inhabited urban and suburban areas within Andean valleys and highlands at 400–3,500 m a.s.l. are home to over 80 million people, almost 40% of the total population of the region (**Table 1**). Furthermore, Andean summits reach peaks higher than 6,500 m a.s.l., while their average altitude is about 4,000 m a.s.l. This topography induces strong disruptions in the atmospheric flow windward and leeward of the cordillera (Garreaud et al., 2009; Arias et al., 2021) (**Figure 1**). Despite outstanding progress in climate models, current simulations over the Andes, although keen at projecting slow varying fields (such as temperature trends), misrepresent precipitation (Zazulie et al., 2017; Díaz et al., 2021; Ortega et al., 2021) and circulation processes that are influenced by topography. These shortcomings hamper our ability to design relevant measures to increase local preparedness to face climate extremes, especially when the topography aspect is factored in.

Although valuable efforts have been done to advance climate research in the region (i.e., Hierro et al., 2020; Flores-Rojas et al., 2021; López-Bermeo et al., 2022), progress has not been as consistent as east of the Andes. For example, a search in scholarly data bases (i.e., Science Direct) shows that for years 2000–2022, the number of publications on topics related to climate and Amazon (18 K) nearly doubles that of climate and Andes (10 K). Partially, the Andean complexity has been overshadowed by more abundant studies and observations in the Amazon for its critical role as a tipping point to the global climate system (Lenton et al., 2019). As a result, we often encounter a disconnect between an Amazon-dominated view of what climate change means to South America and the reality of an entire subcontinent whose weather and climate depend on the Andes. Meanwhile, the region poses unique scientific questions (Wood et al., 2011; Molina et al., 2015; Espinoza et al., 2020; Arias et al., 2021), whose answers are key to the well-being of millions of people due to the climate vulnerability of the region.

While some of the major features of atmospheric dynamics have been described in the literature (Garreaud et al., 2009; Espinoza et al., 2020), the altitudinal gradient induces a variety of weather patterns, both arid and wet, that lack proper understanding and characterization. An aspect that has been readily recognized has to do with climate models falling short at representing the ITCZ

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Table 1. Andean population above 400 m a.s.l. (from national statistics) and share of global emissions as carbon dioxide equivalent (CO_{2eq}; from https://www.climate-resource.com) (Meinshausen et al., 2022)

	Population in Millions		Share of Global Greenhouse Emissions 2030 (2015)	
Country	**400–3,500 m a.s.l**	**Total**	**Per Capita Ton CO_{2eq}**	**%**
Venezuela	8.9	33.4	12.2 (8.5)	0.5 (0.5)
Colombia	31.9	51.6	2.8 (4)	0.3 (0.4)
Ecuador	7.8	17.5	3.1 (4.3)	0.1 (0.1)
Peru	10.0	33.0	2.8 (3.1)	0.2 (0.2)
Bolivia	6.4	12.0	15.1 (11)	0.4 (0.2)
Chile	8.5	19.8	4.9 (6.4)	0.2 (0.2)
Argentina	7.7	46.2	6.9 (8.7)	0.7 (0.8)
Total	81.2	213.6		

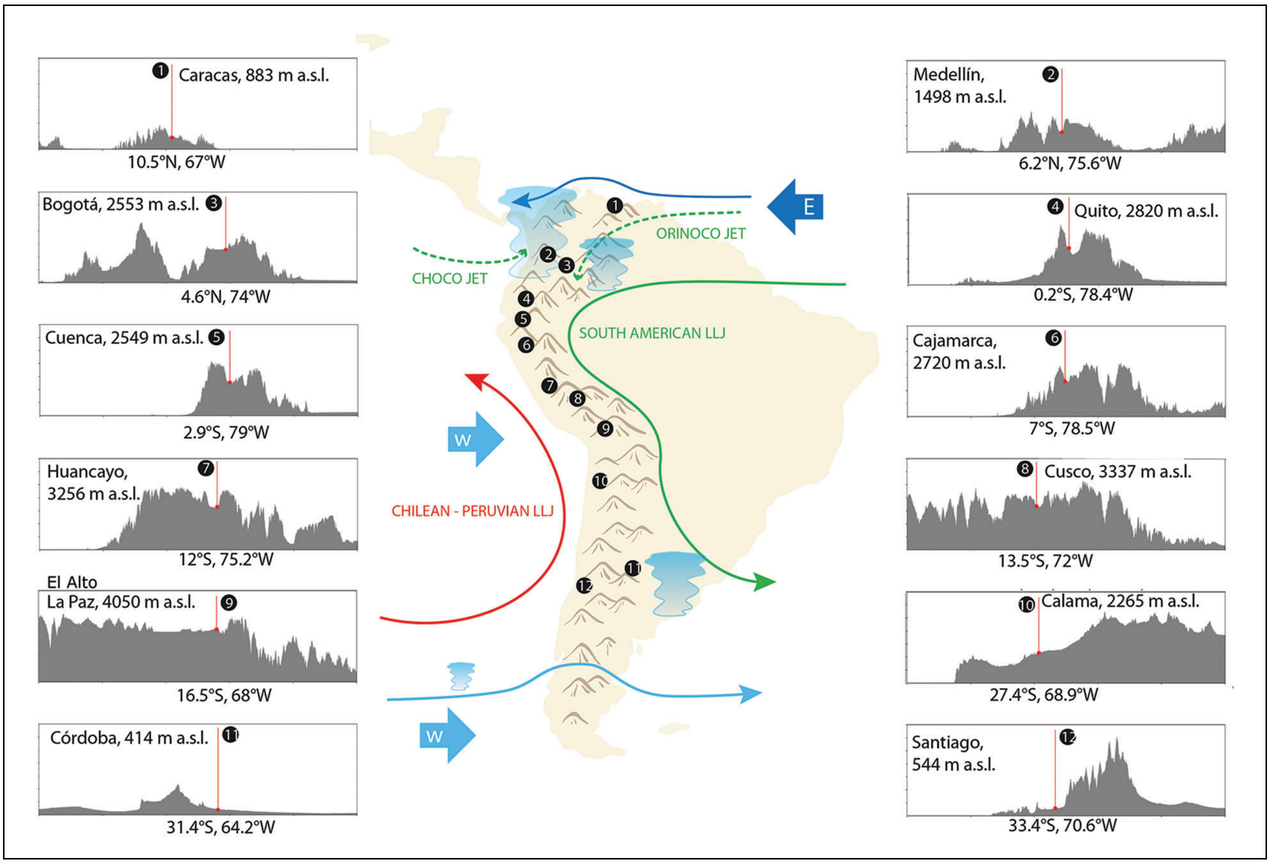

Figure 1. Major circulation features dominated by the Andes and their interactions with the global circulation (adapted from Espinoza et al., 2020). Arrows depict low-level jets, as well as prevalent westerlies (W) and easterlies (E). Deep convection areas are shown as cumulous clouds. East–west topographic cross sections of many of the cities influenced by the Andes are presented on side panels. The altitude scale has been omitted for clarity, but it ranges from 0 to 7 km. Red vertical lines indicate the location of the cities. Cross sections roughly span 5° longitudinally about each city's longitude.

(Ortega et al., 2021), which directly impacts precipitation in northwestern South America. Over the subtropical Andes, climate models also have limitations when representing atmospheric processes (Zazulie et al., 2017; Díaz et al., 2021). Orographic lifting further complicates physical description as it substantially enhances precipitation. An example of feedback between circulation and topography is a Walker circulation-type feature in northwestern South America that causes Colombia's Pacific coast to be the rainiest place on Earth (Poveda and Mesa, 2000; Rojo Hernández and Mesa, 2020). Additionally, the question arises of how precipitation patterns will change in the region due to the amplification of El Niño Southern Oscillation (Poveda et al., 2020), which is projected to occur by the second half of the century (Intergovernmental Panel on Climate Change [IPCC], 2021). The scrutiny of this impact awaits to be addressed in more depth. In contrast, the Pacific Decadal Oscillation, an important driver of climate variability, is well captured in global climate models (Choi and Son, 2022).

Circulation over complex topography not only affects precipitation but also results in low-level jets (LLJs) (Jiménez-Sánchez et al., 2019; Yepes et al., 2019) that expand impacts to the field of air quality. Such is the case of the Orinoco LLJ. This feature transports polluted air masses from Orinoco savanna fires (Hernandez et al., 2019) that seasonally submerge Bogota in air quality emergencies due to high levels of particulate matter (Rincón-Riveros et al., 2020). Another example is poorly characterized intensification of low-level wind from northern Peru, which caused unhealthy air quality conditions in southern Ecuador in early 2022, also due to the transport of particulate matter (Redacción-Cuenca, 2022). Consequently, uncertainties associated to changes in atmospheric motion propagate from the global to the synoptic, and mesoscales within this complex inhabited region.

Downscaling climate projections to levels important to people, property, and ecosystems is urgent to Andean countries, but proper characterization of phenomena at a regional scale is still far from what is needed. For example, tropical Andean countries lack regional weather forecasting models with sufficient data assimilation to quantify risks in the short and long terms. A major factor is a deficiency in coordinated observations (Molina et al., 2015) and sustained modeling efforts. These transnational actions are needed to consolidate surface, radar, and upper-air measurements into much needed regional operational tools. Unfortunately, the magnitude of weather extremes and patterns that are rapidly changing have become evident through major events that have taken a toll on lives and livelihoods. A fatal flash flood and landslide that took the lives of 24 people in Quito, Ecuador (2.78 million inhabitants, 2,800 m a.s.l.) on January 31, 2022 (Petley, 2022), reminded us of how critical weather monitoring combined with proper disaster prevention is in a region that requires a high level of preparedness to combat the strike of climate change (IPCC, 2022).

Incorporating the very complex Andean topography—as a factor that shapes weather and climate in the region—is a task that is yet to be undertaken by coordinated climate research. Among regional efforts, some issues have been more studied than others. For example, the significant concern of depleting sources of fresh water due to the loss of tropical glaciers (Kinouchi et al., 2019) has been documented in the literature not only because of increasing temperature trends but also due to the deposition of black carbon (Rowe et al., 2019), organic carbon, and mineral dust (Gilardoni et al., 2022). Other processes, however, still need to be incorporated into improved evaluations. Hence, we highlight the need for social analysis to inform resilience assessments within countries marked by inequity and political unrest. Likewise, a matter that has fallen behind in receiving attention when dealing with climate change is the issue of air quality in countries that face difficult decarbonization pathways. We elaborate on these points in the following sections.

2. Decarbonization challenges and climate risks in socially conflicted countries

As it is evident in the Sixth Assessment Report (AR6) of the IPCC, ambitious goals of decarbonization are necessary to avoid a climate disaster. Such endeavor calls for global efforts to cut emissions by half within less than 8 years (2030). Argentina, Chile, Colombia, Ecuador, and Peru have sharpened their pledges to the Paris Agreement expecting to reduce their 2030 carbon emissions by 10% to 30% with respect to 2015 (Meinshausen et al., 2022) (**Table 1**). The contrary occurs in the case of Bolivia, Brazil, and Venezuela, whose pledges inform increasing emissions by 10% to 44% with respect to 2015. Brazil and Venezuela are the largest oil producers in South America and stand together for 2.6% and 0.5% of global greenhouse gas emissions, respectively. Colombia, Ecuador, and Bolivia have economies strongly dependent on oil and gas (exports and domestic use). Colombia, Argentina, Venezuela, and Bolivia have well-established pipeline networks for natural gas (NG) distribution (Unidad de Planeación Minero Energética, 2007; Sbroiavacca et al., 2019), which are unlikely to be dismantled in the midterm. Ecuador has been trying to procure investments to increase its oil production, although with opposition by social sectors (España, 2021). Bolivia is also increasing the extraction of NG from its large reserves (Prensa Latina, 2022). Meanwhile, Peru and Chile are net importers of oil, which poses very different incentives for effectively reducing their carbon footprints.

Even though South America is rich in renewables, it is recognized that multiple obstacles exist for proper implementation of these technologies (Levy et al., 2021). Also, hydropower has been a dominant source of energy generation in South America, but climate variability and change have triggered increases in the fraction of power generated by fossil fuels in many countries (Arango-Aramburo et al., 2020). For example, in 2019, hydropower accounted for 55% or more of electricity generation in Venezuela, Colombia, Ecuador, and Peru, and 20%–30% in Argentina, Bolivia, and Chile (**Table 2**) (International Energy Agency, 2019). Other sources of renewable energy for the electrical sector are still marginal in Andean countries except for Chile and Argentina, where wind and solar power have been gaining importance over time. Although these figures are significant, electricity generated by renewable sources is about 10%–22% of the total energy supply in Andean countries. The rest of the energy sectors are still largely dependent on oil and NG. These facts reflect the very different conditions faced by Andean countries when addressing energy transition. A significant challenge is that moving most sectors toward clean energy presents financial, technological, and social barriers that need international investments as those of the Green Climate Fund. However, the size of these funds and their granting mechanisms are still far from the promised figures in Paris.

Table 2. Electricity generation by source in Andean countries in 2019 (from https://www.iea.org/) (International Energy Agency, 2019)

Country		Venezuela	Colombia	Ecuador	Peru	Bolivia	Chile[a]	Argentina[b]
Hydropower	GWh	49,637	54,594	24,663	31,447	3,251	22,477	27,919
	%	58.3	67.9	76.4	55.2	32.0	26.6	20.0
Oil	GWh	14,135	2,725	5,662	697	87	1,170	3,447
	%	16.6	3.4	17.5	1.2	0.9	1.4	2.5
Natural gas	GWh	21,298	13,165	1,390	21,771	6,334	15,865	91,004
	%	25.0	16.4	4.3	38.2	62.3	18.8	65.2
Coal	GWh	–	8,162	–	156	–	28,134	1,260
	%	–	10.1	–	0.3	–	33.3	0.9
Biofuels	GWh	–	1,570	455	507	242	5,394	1,650
	%	–	2.0	1.4	0.9	2.4	6.4	1.2
Wind	GWh	88	63	86	1,654	70	4,897	4,997
	%	0.1	0.1	0.3	2.9	0.7	5.8	3.6
Solar	GWh	9	137	38	779	188	6,419	800
	%	0.01	0.2	0.1	1.4	1.8	7.6	0.6
Total	GWh	85,167	80,416	32,294	57,011	10,172	84,558	139,555

[a] Geothermal generation: 202 GWh (0.2%).

[b] Nuclear generation: 10,707 GWh (6%).

An important angle to consider within the context of decarbonization is social conflict in a region plagued by inequity and unmet basic needs, even more so after the recent COVID-19 pandemic. Government measures related to the economy and potential changes in the cost of energy and transportation are inflammatory issues in Andean countries. For instance, in October 2019, a government attempt to abolish fuel subsidies in Ecuador, although not directly related to climate action, resulted in a violent protest that confronted portions of the population with the police for 12 days and took a destructive toll in historical Quito. The same gloomy picture repeated for 18 days in June 2022, as social sectors demanded lowering gas and diesel prices to compensate for an increase in the cost of living. In Chile, truck companies usually have an upper hand with respect to any government policy related to subsidies, as they control the domestic flow of goods. Colombia, Peru, and Bolivia, due to various reasons, have also had their share of violent protests, which have intensified since 2019. At the same time, strategies to replace fossil fuels in Andean countries are necessary but will have an elevated cost that should not be burdened on impoverished populations. An open discussion on how energy transition will be tackled and how it will be funded is yet to become part of the public debate within societies overwhelmed by political instability and financial distress. This reality of social conflict within a context of inhomogeneous needs to phase out fossil fuel production and consumption is one more downside that places the region behind global trends.

In regard to climate risks and adaptation potential in Central and South America, a recent 10-year literature review (Hagen et al., 2022) states that climate change could severely increase the risk of floods, landslides, water scarcity, and epidemics of vector-borne diseases that would impact the region in diverse ways. Furthermore, these authors indicate that unabated climate change along with a low adaptative capacity will strictly limit options to adjust to new conditions. In part, this low adaptative capacity is explained by a lack of sufficient climate information, as discussed in the previous section. Although there are a variety of measures in place in Central and South America (Castellanos et al., 2022), they are not well suited to face severe risks as they have been adopted as incremental and reactive adaptation measures (Massetti and Mendelsohn, 2018). Moreover, the traditional way of assessing risks is focused on individual phenomena and does not consider compound events that combine climate drivers and hazards (Zscheischler et al., 2018). In cities and urban settlements, vulnerability is enhanced by poverty, informality, inequality, unstable political and governmental institutions, ongoing corruption, reduced capacity to finance adaptation, and so on (Castellanos et al., 2022). In the case of the Andes, the former aspects combined with a lack of adequate climate projections further magnify compound risks. These issues culminate in increased difficulties faced by Andean countries to foresee climate impacts and adapt to future changes.

3. Diverging effects on air quality

According to the IPCC AR6, most mitigation combinations of air pollution and climate change, even if done in different degrees, would bring the benefit of reducing global levels of surface ozone and fine particulate matter ($PM_{2.5}$). However, such projections seem to diverge over Andean countries. While decarbonizing means of transportation would bring the immediate benefit of decreasing $PM_{2.5}$, lessons learned from the 2020 COVID-19 confinements raise an alert of increased ambient ozone in the region, mainly in the event of slow energy transition. The chemistry of ozone production is nonlinear with respect to its precursors, as demonstrated elsewhere (i.e., Kleinman, 2005). During the pandemic lockdowns, a shift in the proportion of traffic associated emissions, namely, volatile organic compounds (VOCs) and nitrogen oxides (NO and NO_2, collectively NO_x), caused the regime of ozone production to shift from NO_x-saturated to NO_x-limited. As a result, ozone production rates increased in places with high NO_x such as Quito (Cazorla, 2021; Cazorla et al., 2021). In Bogotá and Santiago, higher ozone was also recorded because of photochemistry sensitivity to changes in emission precursors during mobility restrictions (Seguel et al., 2022). It is important to remark that currently Bogotá, Quito, and Lima do not have permanent ozone problems, but rather high ozone is recorded episodically. However, ozone could increase in these places if the proportion of urban precursors slowly shifts. In contrast, Santiago has experienced more than two decades of ozone exceedances (Seguel et al., 2020). Recently, it was found that such active photochemistry appears to be leading to an increased fraction of secondary aerosols in spring and summer (Menares et al., 2020). At the same time, air quality is seriously affected by $PM_{2.5}$ pollution in these and many other Andean cities (Gómez Peláez et al., 2020), including the otherwise pristine Patagonia (Solís et al., 2022).

From the points discussed above, transitioning from gasoline- and diesel-based mobility in Andean countries would quickly mitigate $PM_{2.5}$ and primary pollutants, but the effect on ozone chemistry could be counterintuitive. An illustrative example is a modeling study in the city of Cuenca, Ecuador, that shows how the sole measure of replacing the diesel-based public transportation by electric means would decrease $PM_{2.5}$ and NO_2, but the levels of ambient ozone would increase (Parra and Espinoza, 2020). Hence, these complex changes would very likely need to be accompanied by specific controls on NO_x or VOCs in the remaining vehicles, depending on the chemical regime associated to the different stages of transition. Consequently, this problem is intricate. Thus, it needs investment in coordinated modeling and experimental work to understand shifts in the local atmospheric chemistry induced by changes in ozone precursors. The best scenario would be quick and massive decarbonization to rapidly move to a chemical regime that does not risk elevating ozone while it reduces particle pollution. However, chemical transport modeling that is constrained by in situ measurements is urgently needed. Swift energy transition to mend energy poverty is also key to air quality, particularly over more southern latitudes (Reyes et al., 2019; Calvo et al., 2022). Such a plea for massive and well-managed energy transition might seem unrealistic, but it is not less challenging than a fair aspiration of cutting global carbon emissions by half in a matter of just a few years. Hence, this major change should be pursued collectively by Andean countries via access to adaptation funds.

As in the case of atmospheric dynamics, urgent efforts are needed to better understand atmospheric chemistry, even more so if local processes and transitions are combined with the current regime of rapidly changing atmospheric composition. For example, the effect of transport due to increased biomass burning in the region is an issue that needs better representation in global models (Venevsky et al., 2019). This applies to fire modeling and advection processes at the mesoscale and regional scale (Hernandez et al., 2019; Daskalakis et al., 2022). An equally worrisome issue is a lack of background atmosphere observations of short-lived climate forcers along the Andes. In the 7,000 km of the Andes mountain chain, there are only 3 stations for background measurements: Huancayo in Peru, Chacaltaya in Bolivia, and Tololo in Chile. From these stations, Chacaltaya is the only site that has a complete suite of measurements (Andrade et al., 2015; Chauvigné et al., 2019). Immediate consequences of this deficiency in observations are unquantified effects on air quality, misrepresented fields in global models, and a lack of systematic validations of satellite products. This insufficiency hinders air quality assessments needed to devise policies that protect public health on the face of climate change.

4. Final remarks

Unlike many other inhabited regions of the world, the complex topographic and atmospheric circulation conditions of the Andes significantly challenge the level of preparedness needed by countries to cope with climate change. The altitudinal gradient complicates downscaling global models to produce adequate climate and air quality projections. In addition, the region constantly faces social conflict. These difficulties directly affect decision-making processes and climate policy devising. The improvement of climate science in the region cannot continue to be overlooked. Likewise, the implementation of regional climate downscaling and analysis tools cannot continue to be neglected. These are major endeavors that not only demand funding to support regional research but also the will of the community to incorporate science questions unique to the Andes in climate research. At the same time, Andean countries urgently need to coordinate diplomatic actions to secure adaptation funds for climate science as well as for quick and massive decarbonization.

Data accessibility statement

Data on emissions can be found at: https://www.climate-resource.com

Census data can be found at:

http://www.ine.gov.ve/documentos/Demografia/SituacionDinamica/Proyecciones/xls/Entidades/Resumen_Municipios.xls

https://www.dane.gov.co/files/censo2018/proyecciones-de-poblacion/Municipal/anexo-proyecciones-poblacion-Municipal_Area_2018-2035.xlsx

https://www.ecuadorencifras.gob.ec/proyecciones-poblacionales/

https://www.inei.gob.pe/estadisticas/censos/

https://www.ine.gob.bo/index.php/censos-y-proyecciones-de-poblacion-sociales/

https://www.ine.cl/estadisticas/sociales/demografia-y-vitales/proyecciones-de-poblacion

https://www.indec.gob.ar/ftp/cuadros/poblacion/c1_proyecciones_nac_2010_2040.xls

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Competing interests

The authors declare not to have competing interests.

Author contributions

Contributed to conception and design: MC, LG, RJ.

Contributed to analysis and interpretation of data: MC, LG, RJ.

Drafted and/or revised the article: MC, LG, RJ.

Approved the submitted version for publication: MC, LG, RJ.

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