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Pollution and its Impacts on the South American Cryosphere

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Key Points:

- A review of pollution impacts on the Andean cryosphere is presented
- The lack of observations in the Andean region hampers the understanding of glacier retreat
- Few mitigation measures relevant to short-lived climate pollutants have been adopted in the region

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Abstract This article is a review of the science goals and activities initiated within the framework of the **P**ollution and its **I**mpacts on the **S**outh **A**merican **C**ryosphere (PISAC) initiative. Air pollution associated with biomass burning and urban emissions affects extensive areas of South America. We focus on black carbon (BC) aerosol and its impacts on air quality, water availability, and climate, with an emphasis on the Andean cryosphere. BC is one of the key short-lived climate pollutants that is a topic of growing interest for near-term mitigation of these issues. Limited scientific evidence indicates that the Andean cryosphere has already responded to climate change with receding glaciers and snow cover, which directly affect water resources, agriculture, and energy production in the Andean region of South America. Despite the paucity of systematic observations along the Andes, a few studies have detected BC on snow and glaciers in the Andes. These, in addition to existing and projected emissions and weather patterns, suggest a possible contribution of BC to the observed retreat of the Andean cryosphere. Here we provide an overview of the current understanding of these issues from scientific and policy perspectives, and propose strategic expansions to the relevant measurement infrastructure in the region.

1. Introduction

Anthropogenic pollution adversely affects human health and the environment [e.g., *Molina and Molina*, 2004]. Air pollution from biomass burning (BB) and urban emission sources affects large areas of South America, and although it has been a primary concern due to its detrimental health effects [e.g., *Zhu et al.*, 2013 and references therein], other impacts, such as those on the cryosphere and water yield, are becoming focal issues. There is a growing awareness regarding the co-benefits of focusing on short-lived climate pollutants (SLCPs) in order to avoid adverse health effects and climate impacts in the near future [*Anenberg et al.*, 2011; *UNEP*, 2011; *Anenberg et al.*, 2012; *Shindell et al.*, 2012]. SLCPs are harmful air pollutants that also contribute significantly to climate change. The main SLCPs are black carbon (BC), methane (CH_4), tropospheric ozone (O_3), and some hydrofluorocarbons (HFCs). They remain in the atmosphere only for a relatively short time compared to long-lived greenhouse gases. Owing to their nature, these agents can be quickly controlled and reduced with existing technology. For example, Colombia, Ecuador, and Peru are exploring the Reducing Emissions from Degradation and Deforestation Plus program (REDD+) as part of their near-term mitigation plans. The new attainment plans being developed in Chile make an explicit attempt to identify such "win-win" options, e.g., the new Chilean carbon tax recently initiated. These mitigation actions require a sound scientific understanding of the underlying processes leading to air quality degradation and climate impacts by SLCPs, which are largely region and country specific. Given these concerns, an international scientific program designated **P**ollution and its **I**mpacts on the **S**outh **A**merican **C**ryosphere (**PISAC**, http://www.mce2.org/activities/pisac) was launched in October 2013 in Santiago de Chile to address the aforementioned issues. The PISAC initiative is a collaboration of researchers with expertise ranging from the atmospheric and cryospheric sciences to policy making. The overall goal of PISAC is to identify the key sources and impacts of BC and co-pollutants in the Andean region, to initiate research activities at dedicated observation sites in order to close knowledge gaps, and to address mitigation measures for near-term climate protection and air quality improvement. Here we concentrate on the first step in achieving the PISAC objectives, which is to describe the emissions, transport, and deposition of BC and co-pollutants. We describe the current state of research in this specific area and indicate in what direction future research should be focused.

The Andes extend about 7000 km along western South America, spanning tropical, subtropical, and mid-latitude climate to sub Antarctic regimes (see Figure 1). They have an average height of 4000 m a.s.l., with several peaks exceeding 6500 m a.s.l. and glaciers being sustained along almost the whole length of the mountain range. The Andes straddle parts of Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, and Venezuela where approximately 85 million people live [*UNPOP*, 2013]. Moreover, the Andes host the headwaters of major rivers in South America. Snowmelt or runoff from glacier melt is the major source of water for several countries in South America including Chile, Peru, Bolivia, and parts of Ecuador, Colombia, and Venezuela [*Barnett et al.*, 2005]. The relevance of this melt water decreases downstream, particularly in climates dominated by the South American Monsoon System (SAMS) [*Kaser et al.*, 2010]. Thus, glacier retreat and changes in the amount of snow fall and in snow cover duration will have potentially large implications in the availability of water resources for agriculture, industry, energy production, and residential use. A recent report indicates that decreases in water levels in Andean rivers have already led to a 40% reduction in hydroelectricity generation in some regions of Argentina [*WB-ICCI*, 2013]. Some regions of Peru and Ecuador may have already surpassed “peak water” when increased glacier runoff from greater melting begins to decline due to drastic glacier mass reduction [*Baraer et al.*, 2012]. Hundreds of thousands of people living downstream of glacier-fed rivers may face a future of lower stream flow in the warmest months, and seasonal water scarcity as a result.

The environmental and socioeconomic uniqueness of South America make it impossible to accurately infer the issues of priority based on findings in other regions. Although development indicators have generally improved over the last several decades in South America [*UN*, 2013], socioeconomic gradients among countries and inequities within countries are evident and persistent. Such heterogeneities act as amplifiers of environmental problems, leading to differentiated emission patterns, exposure to air pollution, and vulnerability to climate change in urban areas [*Gallardo et al.*, 2012; *Mena-Carrasco et al.*, 2012; *Romero-Lankao et al.*, 2013]. Rural populations are also exposed to air pollution from open burning associated with agricultural practices [*Evangelista et al.*, 2007; *Ignotti et al.*, 2010; *Bell et al.*, 2011; *Jacobson et al.*, 2014] and wood burning used in residential heating and cooking [*Pearce et al.*, 2009; *Alexander et al.*, 2014]. Transport of pollutants from urban emissions sources also impacts rural areas, and vice versa.

Numerous studies have identified adverse health effects from both short-term and long-term exposures to particulate matter less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$), including aggravated asthma [see e.g., *Rabinovitch et al.*, 2006; *Ko et al.*, 2007] and increased cardiopulmonary mortality [see e.g., *Dockery et al.*, 1993; *Pope* Iii, 2002; *Dominici et al.*, 2005]. These small aerosol particles, particularly those that contain BCand other organic carbon (OC) compounds produced during incomplete combustion, contributed to about seven million deaths globally in 2012 due to the combined exposure to outdoor and household indoor pollution [*Lim et al.*, 2012; *Bruce et al.*, 2015]. This finding more than doubles previous estimates and confirms that air pollution is the world’s largest single environmental health risk. *Lim et al.* [2012] found that indoor pollution, mainly associated with cooking and household heating, was ranked as the third largest risk factor to mortality in a systematic analysis for the global burden of disease conducted for the period 1990–2010 for 21 regions. Ambient particulate pollution was ranked ninth out of 43 identified factors. The Andean region was considered separately in that study with indoor pollution ranked seventh and ambient particulate pollution ranked 24th. Six countries in South America are monitoring $PM_{2.5}$, and some already have regulations in place or are in the process of developing them in order to protect the health of their population.

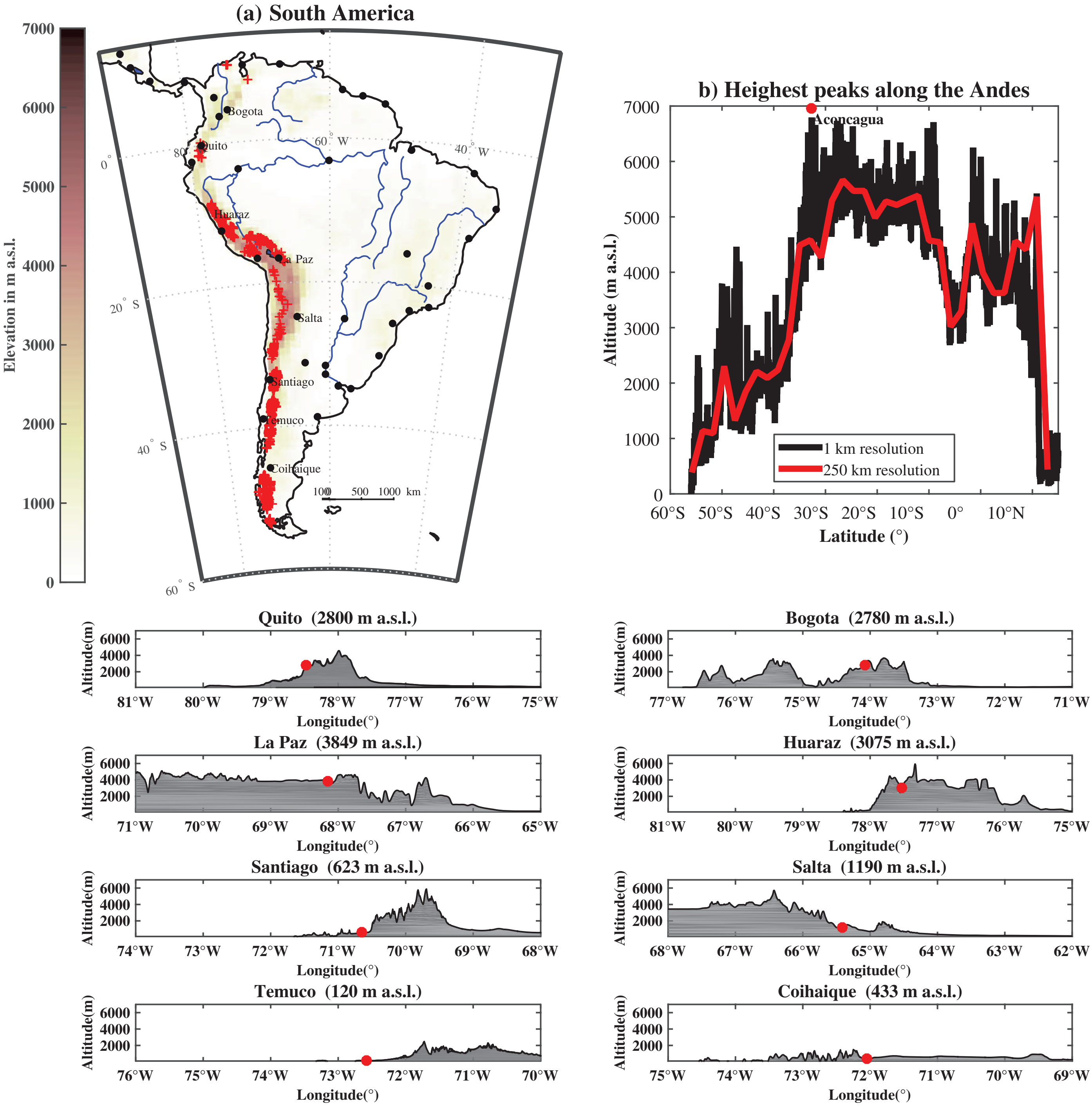

Figure 1. Topographical and physiographical features of South America. Panel (a) shows an elevation map indicating the extent of the Andes as well as major urban centers (black dots), main rivers (blue), and glaciers (red crosses) of South America. A transect of the highest peaks along the Andes at 1 km and 250 km resolution is shown in panel (b). Panel (c) shows latitudinal cross-sections over Bogota, Quito, Huaraz, La Paz, Salta, Santiago, Temuco, and Coihaique in the tropical, central, and southern Andes, respectively. These cross-sections are scaled to 7 km in the vertical axes and six degrees longitude in the horizontal axes, and they are based on topography data from GTOPO30 U.S. Geological Survey (USGS) with a horizontal grid spacing of 30 arc seconds (approximately 1 km). Glaciers and snow cover from http://nsidc.org/data/glacier_inventory/south_america.html.

BC is a solid form of mostly pure carbon that efficiently absorbs solar radiation at all wavelengths [*Petzold et al.*, 2013]. Other carbon-based particulate matter may also be light-absorbing, particularly brown carbon (BrC), which absorbs light within the visible and ultraviolet range of solar radiation and is co-emitted with BC [*Bond et al.*, 2013]. BC is emitted along with other gases and aerosols, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and OC from the burning of fossil fuels (diesel and coal), biofuels (wood, dung, and crop residue), open BB (associated with forest clearing and crop residue burning), wood-burning cook stoves, and burning of urban waste [*Bond*, 2004].

BC has been shown to have a warming influence on the Earth's climate by absorbing solar and terrestrial radiation in the atmosphere on regional and global scales [*Hansen and Nazarenko*, 2004; *Ramanathan and Carmichael*, 2008; *Bond et al.*, 2013]. A more subtle but similarly important impact is the change in surface reflectivity when BC is deposited on snow and ice, darkening the surface and converting the additional absorbed solar radiation to heat that can accelerate the melting or sublimation of snow and ice. This darkening effect is intricate, depending not only on the amount of impurities present but also on factors such as snow grain size, wavelengths absorbed, etc. [*Dang et al.*, 2015]. BC in snow is a concern primarily because of its possible role in altering glacier and snow properties in regions that rely on glacial and snow melt to balance the water supply throughout the seasons [*Bond et al.*, 2013]. The climate efficacy of BC in snow is about 2–4 times that of atmospheric CO_2, so BC in snow has larger climatic effects than its direct radiative forcing would suggest [*Hansen et al.*, 2005; *Flanner et al.*, 2007; *Bond et al.*, 2013]. This aspect has raised interest because it indicates that BC may contribute to an unexpectedly rapid warming of the Arctic and the retreat of glaciers around the world. Glacial retreat has been particularly noted in the Himalayas that experience high levels of pollution and where local populations depend on a seasonally balanced hydrological cycle with glacial melt as a water supply during summer [*Menon et al.*, 2010]. Recent studies show that the wet and dry deposition of BC in the Himalayan mountains and boreal regions may reduce the snow-cover season by up to 10 days [*Ménégoz et al.*, 2013, 2014]. Knowledge of pollutant concentrations and their variability in high mountain regions is therefore essential to better understand the transport of BC and its effect on the cryosphere [*Bonasoni et al.*, 2010].

Although generally hydrophobic when freshly emitted, BC becomes more hydroscopic as it ages due to coatings by more water-soluble compounds [*Liu et al.*, 2013]. Hence, aged BC becomes more active as cloud condensation nuclei (CCN) and can contribute to the hydrological cycle that produces precipitation [*Dusek et al.*, 2006a, 2006b].

There are a variety of emission sources that affect BC presence in the Andean region. BB in the Amazon basin is responsible for about 50% of all BC emissions in the region [*Kesselmeier et al.*, 2009; *Lamarque et al.*, 2010; *Granier et al.*, 2011; *Pereira et al.*, 2011; *Kaiser et al.*, 2012]. Up to the present, urban emission inventories, developed by local authorities in South America, do not regularly include BC. Thus, global inventories provide the only estimate of BC and co-pollutant emissions, covering most of the sources in South America. Nevertheless, it is worth noting that global inventories are based on general methodologies and nationally aggregated statistics that do not necessarily consider regional and local specificities [*Lamarque et al.*, 2010; *Moss et al.*, 2010]. This is particularly relevant in South America for BC emissions. The South American energy matrix is dominated by hydropower (∼50%) and natural gas consumption (∼30%) while the use of coal is less than 2%, in contrast to the global average where coal represents about 40% of the energy matrix [*Sheinbaum-Pardo and Ruiz*, 2012]. Moreover, South America has the largest light-duty vehicle fleet powered by biofuel in the world (Brazil) and one of the highest natural gas consumptions in mobile sources (Argentina) [*D'Angiola et al.*, 2010; *Gallardo et al.*, 2012]. As in the rest of the world, urban and rural wood waste collection for cooking and heating is a common practice; its impact on consumption is rarely considered in the statistics of the different countries, and therefore very difficult to quantify.

A few studies have addressed the transport of pollutants from source regions to the Andes and their potential impacts [e.g., *Andrade et al.*, 2011; *Pereira et al.*, 2011; *Rosário et al.*, 2013; *Mena-Carrasco et al.*, 2014; *Córdova et al.*, 2015). The paucity of studies is partly linked to the lack of observations in the Andean region and also to the difficulties rising from the complex interactions between the airflow and the underlying surface over complex terrain [*Steyn et al.*, 2013].

Several studies have identified changes already occurring in the pattern of stream flow and water quality along the Andes [*Masiokas et al.*, 2006, 2010; *Vicuña et al.*, 2010; *Cortés et al.*, 2011; *Fortner et al.*, 2011;

Pellicciotti et al., 2014]. Regarding attribution studies, atmospheric warming associated with regional climate change has been suggested as the main cause for the fast retreat of tropical glaciers since the mid-1970s [*Rabatel et al.*, 2013]. Precipitation patterns show decreases in intensity and total amount in some sectors [*Carrasco et al.*, 2008; *Schulz et al.*, 2012], and temperature changes leading to changes in precipitation (rain/snow) have also been observed [*Garreaud*, 2013]. *Salzmann et al.* [2013] has found that changes in specific humidity have played a major role in explaining the fast retreat of ice in the Cordillera Vilcanota in the southern Peruvian Andes. Thus, it appears that the main drivers of glacier mass variability are temperature, precipitation, and specific humidity changes. However, it is still unclear how much deposited aerosols contribute to the localized melting process.

With respect to the deposition of light-absorbing aerosols on the Andean cryosphere, various modeling studies, ice core, snow, and firn analyses, and short-term measuring campaigns have addressed long- and short-range transport of BB, and also of urban and wood-burning aerosols [*Kesselmeier et al.*, 2009; *Vimeux et al.*, 2009; *Pereira et al.*, 2011; *Cereceda-Balic et al.*, 2012; *Rosário et al.*, 2013; *Mena-Carrasco et al.*, 2014]. Early signs of the impacts of these aerosols are manifesting themselves on the Andean cryosphere [*Uglietti et al.*, 2015]. In Tierra del Fuego, substantial enrichments of Bi and Cd (hundredfold) point to potential anthropogenic sources [*Grigholm et al.*, 2009]. Recently published results from the analysis of 3 years of measurements (2011–2013) by *Schmitt et al.* [2015] show that glaciers in the Cordillera Blanca mountains close to human population centers have substantially higher levels of BC (up to 70 ng/g) than remote glaciers (2.0 ng/g), indicating that even small population centers can influence local glaciers by contributing to BC emissions. These studies have shown evidence of the potential impact of light-absorbing aerosols; however, the paucity of observations along the Andes precludes a comprehensive assessment of the causes of changes in the Andean cryosphere and prevents the development of appropriate, regionally coherent policy actions. Modeling and attribution studies of the Andean climate are very challenging due to the abrupt topography, leading to complex transport and mixing processes, the need to characterize regional and global anthropogenic signatures, and the lack of observational data that are needed to establish boundary conditions and validate model results. Thus, in this work, we provide an overview of the current scientific understanding of these issues, identify key knowledge gaps, and propose a research strategy for moving the science forward. Moreover, we present a brief review of the currently implemented policies in the Andean countries as well as the strategies being considered for implementation in the near future.

The review is organized as follows: Section 2 summarizes the climate studies on the South American cryosphere; changes in the Andean cryosphere and the impacts on watersheds are discussed in Section 3; Section 4 describes emission processes and their quantification as well as examples of relevant policy actions; existing and required observations that address BC impacts in the region are discussed in Section 5; and Section 6 summarizes and concludes this review.

2. The Climate of the Andean region

An extensive review of climate in the Andes is given by *Garreaud et al.* [2009]. Here we highlight the meteorological processes that are most relevant for understanding how the snow fields and glaciers form and change. Climatologies of relevant variables are shown in Figure 2. At middle and upper levels, the Andes are exposed to moderate easterly winds at low latitudes and westerly winds at subtropical/extra-tropical latitudes (not shown). In the austral summer, a light easterly flow extends down to 21°S. An important factor in the southward extent of the easterlies is the establishment of the upper-level Bolivian High (BH, centered at 17°S, 70°W). During summer months, the subtropical westerly jet weakens and reaches its southernmost position. In contrast, during winter, easterly winds are restricted to the north of 10°S, and the subtropical westerly jet becomes stronger with its core at 30°S. Low-level flow (below ~1.5 km) near the Andes is more complex than its upper-level counterpart. The Southeast Pacific anticyclone leads to southerly winds that are mostly parallel to the west coast of South America at tropical and subtropical latitudes [*Muñoz and Garreaud*, 2005]. This coastal area features an extremely arid and stable environment [*Rutllant*, 2003]. Above 2000 m on the western slope of the mountain range, the winds reverse, and there is an elevated northerly jet at about 3000 m a.s.l. resulting from the mechanical blocking of the Andes on the prevailing westerly wind in the middle troposphere [*Kalthoff et al.*, 2002; *Rutllant and Garreaud*, 2004].

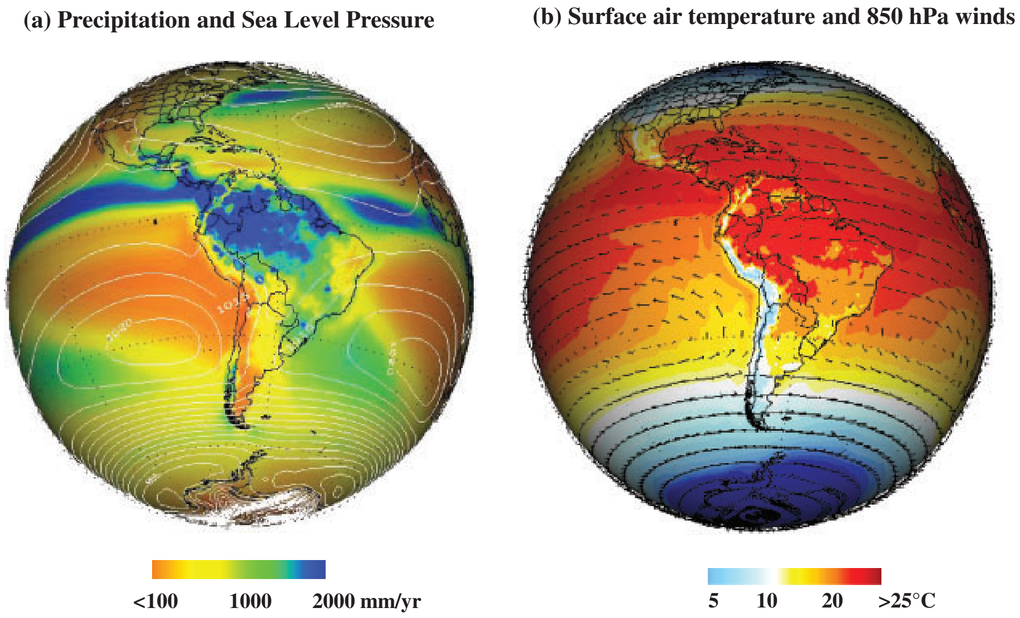

Figure 2. Long-term climatology (1981–2010) of South America. The left panel shows the annual precipitation in mm/yr (color scale at bottom) from the Global Precipitation Climatology Project (GPCP) [*Adler et al.*, 2003] over the ocean and the University of Delaware (UDel) [*D. R. Legates and C. J. Willmott*, 1990a; *David R. Legates and Cort J. Willmott*, 1990b] over the continent. Also shown is the sea level pressure from the NCEP/NCAR reanalysis (NNR) [*Kalnay et al.*, 1996] contoured every 2.5 hPa. On the right panel, annually averaged surface air temperatures (color scale at bottom) from NNR over the ocean and UDel over land. Arrows shows the 850 hPa (about 1500 m ASL) winds from NNR.

Over the interior of the continent, where much more humid conditions prevail, the trade winds enter the continent near the equator reaching the eastern slopes of the tropical Andes and are subsequently deflected toward the south. Such terrain-parallel low-level airflow often results in low-level jets [*Vera et al.*, 2006a, 2006b] that transport moisture and other tracers from the Amazon basin into the subtropical plains east of the Andes [*Freitas et al.*, 2005]. The terrain-parallel airflow on both sides of the Andes is a reflection of the blocking exerted by the tropical and subtropical Andes on the large-scale flow.

South of about 40°S, the height of the Andes drops to less than 1000 m a.s.l. (except for some isolated peaks), and the westerly winds flow nearly perpendicular to the southern and austral Andes, bringing pristine air from the Pacific Ocean. The seasonal variations of the aforementioned low-level circulation pattern are rather minor.

Precipitation over the tropical Andes is dominated by the influence of the Inter Tropical Convergence Zone (ITCZ) and the SAMS, occurring in the austral summer [*Marengo et al.*, 2012]. Precipitation over the Andean Altiplano shows significant spatial variability [*Garreaud and Aceituno*, 2001]. In the subtropical Andes, precipitation occurs in connection with deep troughs and cold fronts in winter, with significant variability linked to the El Niño Southern Oscillation [*Montecinos and Aceituno*, 2003; *Falvey and Garreaud*, 2007; *Rutllant and Fuenzalida*, 2007; *Quintana and Aceituno*, 2012]. Over the southern Andes, there is rainfall all year round in connection with synoptic disturbances brought by the westerlies [*Berman et al.*, 2012; *Garreaud et al.*, 2013]. These patterns are strongly modulated by topography [*Bookhagen and Strecker*, 2008].

In addition to these large-scale characteristics, mountain-valley circulations develop daily in response to the land heating over the tropical and subtropical Andes. The relatively cool conditions at nighttime result in drainage flows from the Andes toward both sides. The downslope flow is rather weak and prevails until early morning when the subsequent warming of the terrain leads to stronger upslope flows from both sides, converging just atop of the Andes. The strong (weak) upslope (downslope) flow during the day (night) is a robust feature in low-latitude mountains because of the intense surface heating. The detailed distribution, timing, and intensity of the wind are, however, much less explored in the Andes. Of particular interest are the differences in the airflow channeled by the narrow valleys by comparison to those that develop over more open terrain [*Steyn et al.*, 2013]. The complex topography of the region is illustrated in Figure 1.

The impact on the Andean cryosphere from emissions of urban and agricultural areas in the lowlands depends on the regional air flow and the development and vertical extent of the boundary layer over those areas [*Weissmann et al.*, 2005; *Fast et al.*, 2012]. The diurnal evolution of the boundary layer is modulated by insolation, surface winds, stratification, land use, surface roughness, topography, anthropogenic heat, synoptic, and sub-synoptic phenomena. Large urban areas are located within or near the Andes (e.g., Santiago, La Paz, Quito, and Bogota), but there are a few studies that have characterized the atmospheric boundary layer in the complex terrain close to the Andes, mostly due to the lack of vertically-resolved observations [*Muñoz and Undurraga*, 2010; *Andrade et al.*, 2011; *Toledo and Gustín*, 2011; *Muñoz et al.*, 2013; *Nisperuza*, 2014]. Current models provide sophisticated parameterizations of boundary layer processes, but their validation is limited by the lack of systematic and long-term observations at different altitudes [*Freitas et al.*, 2006; *Saide et al.*, 2011a, 2011b]. Considering boundary layer processes and heat release in connection with BB is also key to adequately representing the medium and long-range transport of pollutants [*Freitas et al.*, 2007].

Variability and changes in circulation and precipitation patterns are also important with respect to the processes leading to emissions. For instance, recent work shows that the duration of the dry season over southern Amazonia has increased significantly since 1978 [*Fu et al.*, 2013; *Arias et al.*, 2015]. This has repercussions for seasonality and long-term changes in the carbon cycle at large and organic and BC emissions in particular due to increased fire activity [*Malhi et al.*, 2009; *Silvestrini et al.*, 2011; *Saatchi et al.*, 2013].

3. Glaciers and Watersheds

The Andes Cordillera is typically divided between the tropical Andes (10°N–17°S) and the southern Andes (18–56°S) (see Figure 1). The southern Andes (18–56°S) can be divided into the dry Andes (18–34°S) and the wet Andes (35–56°S) [*Lliboutry*, 1998]. Moreover, the dry Andes, located in the “Arid Diagonal” of South America [*Vuille and Ammann*, 1997], can be divided further into the desert Andes (18–31°S) and the central Andes (31–34°S). In agreement with the global trend, a generalized and accelerated glacier recession has been occurring both in the tropical and the southern Andes [*Casassa et al.*, 2007; *Rabatel et al.*, 2013]. In many cases, glacier loss rates in the Andes have accelerated in recent years [*Le Quesne et al.*, 2009; *Rivera et al.*, 2012; *Willis et al.*, 2012; *Rabatel et al.*, 2013]. *Zazulie* [2015], through the analysis of Landsat imagery, reported the decreasing areal extent of glaciers in the region between 30°S and 37°S. It has to be noted that in the far south, there are a few examples of glaciers with stable fronts or even advancing fronts in Patagonia and Tierra del Fuego [*Casassa et al.*, 2014; *Schaefer et al.*, 2015].

The stability of glaciers largely depends on the glacier mass balance, which is a critical link between the atmosphere and the glacier surface. It is defined as the net change in mass between two successive periods, considered normally as one calendar year [*Østrem and Brugman*, 1991]. The most important process of mass accumulation is the deposition of snow [*Benn and Evans*, 2010], which is directly related to atmospheric circulation and precipitation and its interaction with the local relief [*Oerlemans*, 2001]. Ablation, which refers to the removal of snow and ice of a glacier, occurs mainly due to melt followed by runoff but can also be affected by wind action, ice calving in freshwater or tidewater, and sublimation that can be very relevant in dry high-altitude environments [*Benn and Evans*, 2010, 2014]. An important process of melting glaciers is determined by the energy balance in the surface–atmosphere interface [*Braithwaite*, 1995; *Oerlemans*, 2001]. A major part of the solar energy reaching a glacier can be reflected depending on the surface albedo, which ranges from 0.85 in fresh dry snow to 0.20 in debris-rich ice [*Cuffey and Paterson*, 2010]. Because of these large changes in surface albedo, the deposition of dark material such as dust and other light-absorbing aerosols can also contribute to changing the pace at which glaciers melt [*Brock et al.*, 2007; *Bond et al.*, 2013; *Ménégoz et al.*, 2014; *Arenson et al.*, 2015]. A glacier’s upper zone where accumulation dominates is separated from its lower zone where ablation dominates by an idealized line called the Equilibrium Line. In the Andes, the Equilibrium Line Altitude (ELA) ranges from >5000 m in the tropical Andes to approximately 1000 m in southern Patagonia and Tierra del Fuego. Glacier mass balance and ELA are closely linked to climate and are therefore subjected to interannual and interdecadal and longer-term variability, leading glaciers to naturally grow and retreat. However, the growth and decay rate of glaciers also depend on ice dynamics, glacier geometry, and basal conditions, which can be completely different from one valley to another even though they share the same climatic variability.

The Andes host the largest concentration of tropical glaciers in the world. These glaciers have been retreating at an accelerating rate since the seventeenth century [*Rabatel et al.*, 2013]. Small glaciers located at relatively low elevations are vanishing, particularly those where the ELA lies above the highest summits, such as the Chacaltaya glacier in the Cordillera Real, Bolivia, which disappeared in 2010 [*Rosenzweig et al.*, 2008]. Mass balance losses have more than tripled in the period 1976–2010 (−0.76 m water equivalent per year) compared to 1964–1975 (−0.2 m water equivalent per year) and have increased even more since 2000, mostly due to warming trends in this region [*Rabatel et al.*, 2013; *Vuille et al.*, 2015].

Practically no glaciers exist at the Tropic of Capricorn as the ELAs lie above the altitude of the highest peaks [*Carrasco et al.*, 2008]. Frontal systems are the main source of precipitation in the central and the wet Andes, with ELAs and mountain elevations dropping gradually to the south. In most cases, retreat rates in the dry and wet Andes have accelerated in recent years, with mass balance measurements showing negative trends during the last few decades [*Magrin et al.*, 2014; *Pellicciotti et al.*, 2014]. Large tidewater and freshwater glaciers in Patagonia and Tierra del Fuego are experiencing large retreat, although in addition to climate forcing, geometrical and dynamic factors may also be important, particularly in the case of calving glaciers [*Casassa et al.*, 1997; *Porter and Santana*, 2003; *Rivera et al.*, 2012]. Accelerated thinning is also occurring in Patagonia, with values of several meters per year up to a maximum of 30 m/year [*Rignot et al.*, 2003]. In at least a few glaciers, such as Jorge Montt, ice velocities have doubled during the last two decades, so creep thinning has played a crucial role in the glacier loss [*Mouginot and Rignot*, 2015]. Pío XI and Perito Moreno glaciers in Patagonia represent examples against the trend that are stable or even advancing [*Casassa et al.*, 2014]. In southern Patagonia and Tierra del Fuego, enhanced westerly circulation [*Mayewski et al.*, 2013] may cause increased precipitation, which may result in positive mass balance, although this has not been detected yet.

Trends in snow cover and glacier extent are predominantly linked to changes in meteorological conditions (temperature, precipitation, winds). For example, it is most probable that temperature rise is also the major driver of glacier mass loss in the southern part of the Andes [*Rivera et al.*, 2002], although reduced precipitation may have contributed in specific areas [*Carrasco et al.*, 2008]. However, glaciers in different climatic regimes may not react similarly to identical perturbations [*Rupper and Roe*, 2008]. To address the wide variability of temperature and precipitation in South America (cf. Figure 2), *Sagredo and Lowell* [2012] identified three main climatic conditions along the Andes that can sustain glaciers: warm and wet, intermediate, and cold and dry, located predominantly in the wet, tropical, and dry Andes, respectively. Because these glaciers are sustained by different influence levels of temperature and precipitation, their reaction to variations in these variables is not uniform. In general, glaciers in areas with high and low precipitation are more sensitive to temperature and precipitation changes, respectively [*Rupper and Roe*, 2008].

Particularly in the dry Andes and parts of the tropical Andes, glaciers can be important water sources during the dry season [*Casassa et al.*, 2009; *Ohlanders et al.*, 2013] along with snowmelt [*Vicuña et al.*, 2010]. Glacier hazards such as glacial lake outburst floods, ice avalanches, and glacier slides can also become more frequent under warmer conditions [*Kaltenborn et al.*, 2010]. Considering the impacts of warming at high elevations, including snow line rise and glacier retreat, there is a real need for planning and adaptation measures regarding water resources and glacier hazards [*Vergara et al.*, 2007; *Salzmann et al.*, 2009].

The discharge changes related to glacier retreat can be conceptualized following the model of *Baraer et al.* [2012]: Phase 1 (early stages of glacier retreat)- annual and dry season flows gradually increase while the annual discharge coefficient of variation decreases to a minimum, consistent with increased contribution of ice melt to river flow; Phase 2 (increase in the coefficient of variation): annual flow reaches its maximum while dry season flow begins its decline; Phase 3 (high coefficient of variation, tipping point): both annual and dry season flows decrease sharply; Phase 4 (glaciers no longer have a hydrological role in the basin): asymptotic stabilization of annual and dry season flows at lower levels than the pre-retreat values. In this model, initial glaciated area and annual ice area loss are more important than the total watershed area in determining glacier influence on hydrology. An analysis of nine basins in the Cordillera Blanca, Peru showed that seven of these can be considered to be in Phase 3, i.e., in a phase of irreversible change.

Although sharp decreases in glacier area have been documented in extra-tropical glaciers of Chile and Argentina [*Vuille et al.*, 2008; *Masiokas et al.*, 2009; *Pellicciotti et al.*, 2014], the potential effects on local hydrology is less understood. Limited available observations make the interpretation of historical records a challenging task. For example, although warming at high elevations of the southern Andes has been documented during the last 40 years, no significant evidence of trends in annual river flows such as those observed in the Cordillera Blanca has been detected [*Casassa et al.*, 2009; *Cortés et al.*, 2011]. As shown by *Ragettli et al.* [2014], adequate representation of glaciohydrological processes is key for the reliable modeling in Andean basins and, in turn, for water resource climate change impact and adaptation studies.

In this context, accurate characterization and modeling of dust and BC deposition on snow and ice surfaces is paramount. *Yasunari et al.* [2010] estimated that BC concentrations between 26 and 68 μg/kg could result in a range of 2.0–5.2% albedo reductions. Through simple glacier mass balance modeling, they translated these albedo reductions to increases in annual runoff equivalent to between 11.6 and 33.9% of a typical Tibetan glacier. More recently, *Kaspari et al.* [2014] demonstrated that deposited impurities can have significant impacts on snow albedo, representing localized instantaneous radiative forcing of up to 525 W/m^2 in some cases. This additional forcing clearly has an impact on melt rates, affecting glacier annual mass balance and the timing of the melt hydrograph in snow-dominated basins. Very little is known about these processes for the cryospheric systems along the Andes cordillera, which sustain water resources for millions of inhabitants of the South American Pacific rim.

4. Emissions of Black Carbon

Regional estimates of BC emissions are scarce and fragmented. Countries report emissions of carbon monoxide, nitrogen dioxides, total hydrocarbons, and sulfur dioxide within the framework of the National Communications under the United Nations Framework Convention on Climate Change (UNFCCC). Environmental authorities contract developments of emission inventories for criteria pollutants in some cities and for some industrial centers [*Zhu et al.*, 2013], but few include BC.

Owing to the absence of consistent and coherent regional inventories, we make use of several contemporary global emission inventories for anthropogenic BC [*Lamarque et al.*, 2010; *Bond et al.*, 2013]. Some of these inventories are available at Emissions of Atmospheric Compounds & Compilation of Ancillary Data (ECCAD, http://eccad.sedoo.fr/), and they are used here to illustrate the contribution of anthropogenic sources to BC emissions in South America. Emissions from BB are provided by two inventories used extensively in the modeling community, namely, the Global Fire Emissions Database (GFED) described by *van der Werf et al.* [2010a, 2010b] and the Global Fire Assimilation System (GFAS) presented by *Kaiser et al.* [2012].

In addition to global estimates, it is worth noting that regional emissions inventories associated with vegetation fires are produced by the Brazilian Biomass Burning Emission Model (3BEM) [*Pereira et al.*, 2009, 2011]. These estimates have been validated against carbon monoxide measurements collected in aircraft experiments [*Archer-Nicholls et al.*, 2015], showing encouraging results. The scientific community has also been improving regional estimates for BB [*Pereira et al.*, 2009; *Longo et al.*, 2010] and urban emissions [*Toro et al.*, 2006; *Zarate et al.*, 2007; *Alonso et al.*, 2010; *D'Angiola et al.*, 2010; *Saide et al.*, 2011a 2011b; *Gallardo et al.*, 2012].

Anthropogenic sources presented here include fuel combustion in stationary and mobile sources and industrial processes, while the open burning of agricultural residues and the prescribed burning of savannas and forest fires are counted as BB sources. Figure 3 shows the spatial distribution of anthropogenic and BB emissions for year 2000 according to *Lamarque et al.* [2010]. In this estimate, BC emissions in South America amounted to 0.75 Tg of which BB accounted for 55% and anthropogenic sources for the remaining 45%. Figure 4 shows the evolution of these emissions during the twentieth century and the contributions of different sectors to total BC emissions worldwide and for South America. In South America, the major sources after BB are diesel transport and the use of carbon in industries, with a lesser contribution from residential heating, whereas worldwide BB and residential heating are of similar importance. It should be noted that these estimates are based on nationally aggregated statistics of energy consumption, which do not take proper account of residential heating and cooking and informal industries, such as brick kilns, thus possibly leading to an underestimation of emissions.

4.1. Biomass Burning

BB and open agricultural burning are common practices not only in the Amazon basin but also in many other areas of South America [*Korontzi et al.*, 2006; *Le Page et al.*, 2010; *Magi et al.*, 2012]. Actively burning fires

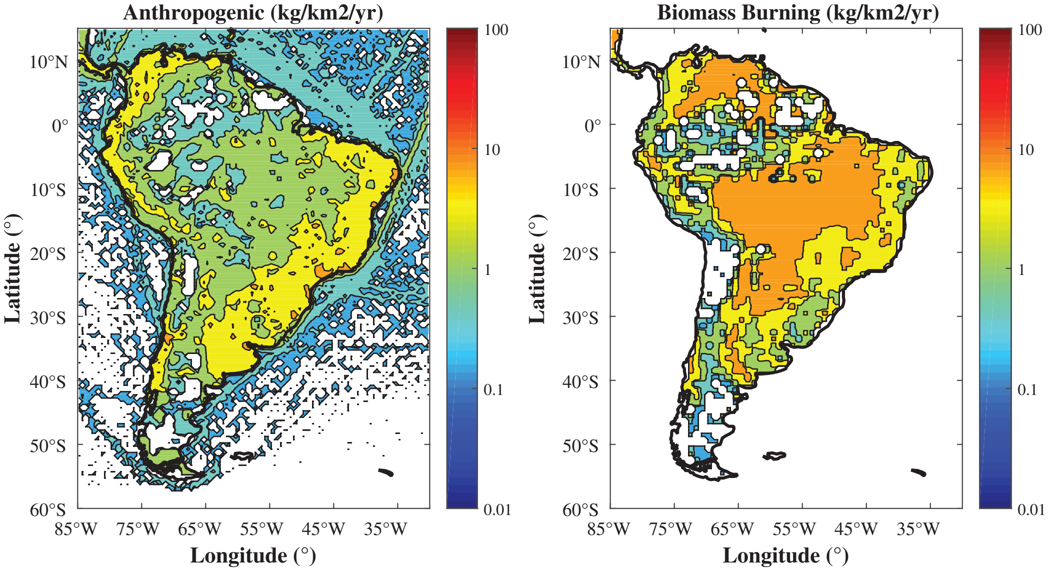

Figure 3. Spatial distribution of black carbon emissions (in kg/km^2/yr) for South America according to the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) for the year 2000 [*Lamarque et al.*, 2010] and available at http://eccad.sedoo.fr. The left panel depicts anthropogenic sources (fuel combustion excluding open burning), and the right panel shows biomass burning fluxes.

in the Andean Region and in the countries of Bolivia, Chile, Colombia, Ecuador, and Peru shows a marked increase in detected fires during the Southern Hemisphere spring (August–November) as well as some during fall in March and April, specifically near the Equator (see Figure 5). Much of this Southern Hemisphere spring burning occurs in evergreen broadleaf forests and croplands land cover classes while the Southern Hemisphere autumn burning near the Equator occurs in savannah/grasslands and croplands land cover classes (cf. Figure 3). Burning in the tropical savannah constitutes a significant source of pollutants in the region [*Sanhueza et al.*, 1999] that reaches the tropical Andes [*Hamburger et al.*, 2013]. In addition, pollution from burning in the lowlands of Bolivia [*Pinto-Ledezma and Rivero Mamani*, 2013] has been shown to reach the high Andes [*Andrade et al.*, 2011].

South American BB emissions grew from about 0.30 Tg BC in 1950 to 0.45 Tg BC in the 1990s according to *Lamarque et al.* [2010], driven by changes in the Amazon basin. Deforestation of tropical forest and savanna and grassland fires are the two main contributors of BC emissions arising from BB in South America, representing more than 90% of the total BB emissions. Forest exploitation, associated with agriculture, biofuel, and timber production and expanding populations, is a major factor contributing to deforestation in Brazil [*Matza*, 2013]. However, based on satellite data, these deforested areas in the Amazon have been showing a decreasing trend since 2004 [*Câmara et al.*, 2013] due to the adoption of measures taken by the Brazilian government. Yet, based on estimates by *van der Werf et al.* [2010a, 2010b], BC emissions from tropical forest fires in South America have not followed the same reduction trend seen in deforested areas.

Estimating emissions from BB requires knowledge about the amount of biomass burnt per unit area and time as well as the burning conditions [*Liousse et al.*, 2004]. Given the spatial and temporal variability of fire emissions [*Castellanos et al.*, 2014], satellite sensors provide a good approach to monitor this phenomenon on the global scale. However, these studies require high-resolution data for calibration [*Boschetti et al.*, 2004] and revision of emission factors that can only be provided by *in situ* measurements and long-term monitoring in the region.

4.2. Anthropogenic Emissions

According to *Lamarque et al.* [2010], anthropogenic emissions of BC in South America grew rapidly in the second half of the twentieth century from 0.05 Tg BC in 1940 to 0.3 Tg in the late 1990s. This follows the region's population growth as well as its industrial and urban development.

In urban areas, emissions of BC are linked to diesel vehicles, residential burning of wood and waste for heating and cooking, and informal brick production. As previously indicated, BC emissions are generally not

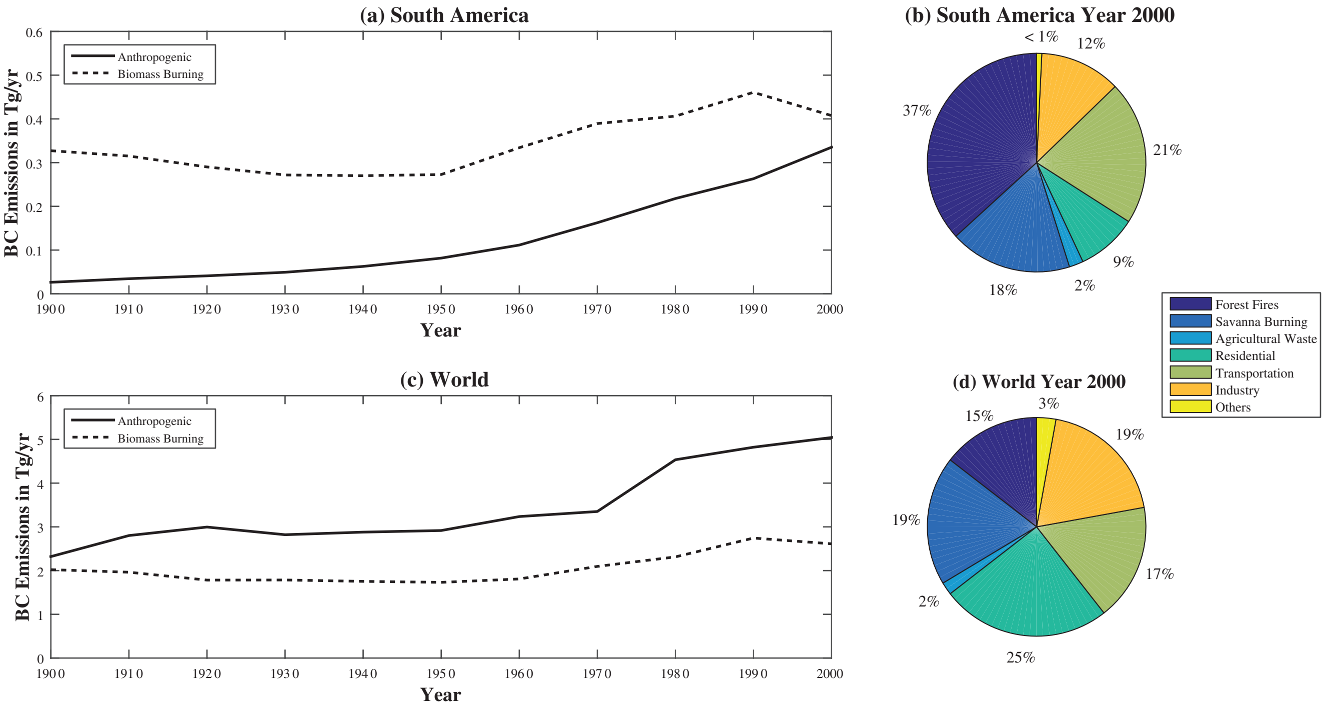

Figure 4. Temporal evolution during the twentieth century and year 2000 distribution by sector of black carbon emissions in South America and the world in panels a and b and c and d, respectively. Anthropogenic emissions include residential, transportation, industry, energy, aviation, ships, and waste sectors, whereas biomass burning includes forest fires and savanna burning. The category "others" in the pie charts lumps aviation, ships, energy, and waste sectors. Data according to [*Lamarque et al.*, 2010].

considered in current urban emission inventories in South America. The practice to infer BC fluxes in urban areas from down-scaling global anthropogenic emission estimates may introduce an important and significant bias in the inventory. Nationally aggregated statistics on fuel consumption and traveled distances by diesel-powered vehicles are used to estimate BC emissions globally. These statistics are largely dominated by heavy-duty diesel trucks (HDDTs) transporting goods. Yet the emissions are spatially distributed using population density as a proxy. Given that most of the HDDTs' emissions occurs outside of urban areas, such approaches result in an overestimation of BC emissions at the city scale and an underestimation outside of them. A study in Sao Paulo has shown that HDDTs are major emitters on the city scale [*Andrade et al.*, 2012].

Diesel freight truck transport across the Andes may also be a locally relevant source of BC. For example, the annual average daily traffic of vehicles crossing the Andes at Cristo Redentor was approximately 2000 in 2012 (http://servicios.vialidad.cl/censo/), of which about half were trucks and buses. This passage is near the Aconcagua peak, crossing the Andes at 3000 m a.s.l. While in absolute terms, these sources may be small, their emissions at high elevation make them more likely to have a relatively large impact on the nearby cryosphere. A similar situation may occur in connection with the diesel trucks used in widespread mining activities at high elevation.

In current global inventories, BC emissions from residential areas are estimated to be less than 10% of the regional emissions in South America (cf. Figure 4). These sources are nevertheless poorly constrained as they require the determination of local emission factors and activity data, a pending task for policy and research communities in the region. The challenge arises from the probable impacts of these sources, especially on human health, and their occurrence in the nearness of the Andean cryosphere.

As mentioned above, household air pollution causes about 4 million premature deaths and 4.8% loss of healthy life years worldwide [*Smith et al.*, 2014]. *Bonjour et al.* [2013] show declining trends in the use of solid fuel for cooking in the Americas. However, wood burning for cooking and heating is still a common practice in countries along the Andes, both in high-altitude villages and cities and in large lowland urban centers, particularly in the southern part of South America, posing significant health risks for its population. According to the WHO statistics for 2013, Peru, Bolivia, and Colombia showed the largest percentages of

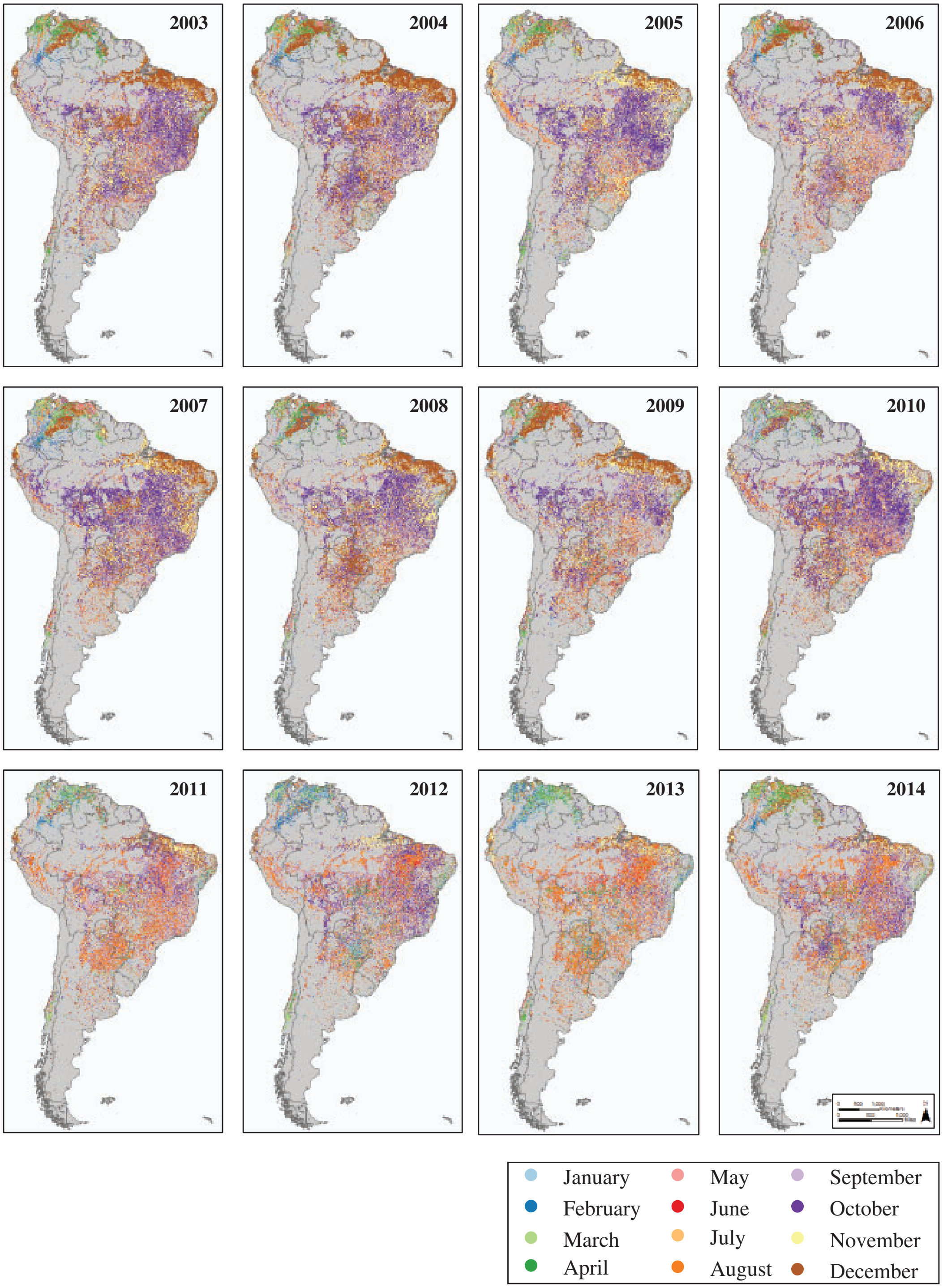

Figure 5. Monthly fires across all land cover types as detected by the MODIS Active Fire product in the Andean Region, 2003–2014.

population using solid fuels along the Andes, corresponding to 34, 23, and 14%, respectively [*WHO*, 2015]. Interestingly, economic development of a country and the rise in household income do not determine the changes in the energy consumption [*Heltberg*, 2004], and residential wood burning is present in low-income rural households [*Alexander et al.*, 2014], high-income urban homes [*Mena-Carrasco et al.*, 2012], and as part of commercial cooking [*de Albuquerque Sgarbi et al.*, 2013]. Moreover, wood burning typically occurs in conditions of poor atmospheric ventilation, i.e., in the cold season and during nighttime and early morning, leading to enhanced concentrations and adverse health effects [*Saide et al.*, 2011a 2011b; *Mena-Carrasco et al.*, 2012].

Brick production in rudimentary kilns is also a significant source of BC and other pollutants in many urban and peri-urban areas of the world and is associated with adverse health impacts [*Schmidt*, 2013]. Estimating this source is nevertheless very difficult due to their lack of formal oversight and to the wide range of firing conditions and fuels used. Modernizing traditional brick kilns and coke ovens has been suggested as a mitigation opportunity for BC emissions on the global scale [*UNEP*, 2011]. Such opportunities are being explored in various countries in South America (http://www.redladrilleras.net).

4.3. Future Emissions Trends

BC emissions in developed countries have been reduced since the mid-2000s by the implementation of regulatory measures mainly in the transport sector and also due to declines in the traditional use of biomass for residential combustion [*UNEP*, 2011]. For these countries, it is expected that this trend will continue with the incorporation of new planned regulations and improved technologies. Future emission scenarios for other regions, including South America, have been built considering that similar policies are expected to slow down their future rate of emissions growth. In fact, the Representative Concentration Pathways (RCP) corresponding to an 8.5 W/m2 forcing (RCP8.5) projection considers a decrease of approximately 0.05 Tg/year for South America from 2005 to 2010. However, as the more recent inventory from *Wang et al.* [2014] illustrates, BC emissions have been increasing steadily since 2000. Differences between these inventories is strongly linked to the different assumptions made when building them. Therefore, the emission projections for South America as well as the assumptions behind them need to be revisited and updated using available local information. Part of this information and changes in future emissions to come will emerge from the policies implemented in South American countries in addition to technological changes, such as those illustrated in the following section.

4.4. Mitigation Policies in Andean Countries

The global assessment by the United Nations Environmental Programme has identified some measures for BC control that would provide local benefits to Latin America and the Caribbean in general, and South America in particular [*UNEP*, 2011; *Shindell et al.*, 2012]. However, this assessment was made using global climate models with very coarse resolution, so the Andes were not resolved adequately. Moreover, the emissions and mitigation measures considered were grouped together in only a few countries (Brazil, Argentina, Chile, and one category for the rest of Latin America and the Caribbean). These measures address, among others, the use of diesel particle filters, elimination of high-emitting vehicles, replacing coal by coal briquettes in stoves, improved brick kilns, introducing end-of-pipe abatement measures in coke ovens, and banning open field burning of agricultural waste. The applicability of measures identified on the global scale will depend on the political, cultural, and socioeconomic considerations of each country, and they will require a thorough evaluation of their efficacy and validity. High-resolution modeling studies will be needed to assess the extent to which these measures will be adequate in reducing impacts on the Andean cryosphere in different regions along the Andes.

A cursory review of national action plans in the framework of the UNFCCC, as well as plans for air quality attainment in each of the seven Andean countries, indicates a variety of activities that may lead to the reduction of BC and co-emitted pollutants. All Andean countries have different programs defined to promote and/or develop measures for the reductions of carbon emissions, with a focus on carbon dioxide, including clean development mechanisms. Many of the countries have air quality attainment plans in place for major urban centers, including particulate matter (PM). Some of the measures considered in these frameworks will help reduce BC emissions although they are not designed specifically to abate BC and co-emitted pollutants nor have they been evaluated with respect to their efficacy.

In the context of air quality management in urban areas along the Andes, one can find measures that are directly relevant for BC and other SLCPs. For example, Chile has recently introduced a tax reform (Law 20.780) that, among other things, establishes tariffs for emissions from stationary sources, power plants in particular, and upon the importation of highly polluting light vehicles, as measured per their emissions of nitrogen oxides, which will primarily affect cars using diesel. Also, attainment plans to be developed for urban centers in central and southern Chile will address the issue of wood burning by means of structural changes in energy supply and insulation of houses [*MMA*, 2014]. In addition, some cities such as Bogota and Santiago have developed mass-transportation systems (*TransMilenio* and *TranSantiago*, respectively) as part of the initiatives to mitigate air pollution and vehicular congestion. In the case of Santiago, roughly half of the bus fleet has diesel particle filters. However, such efforts are not widespread in the Andean region.

Many governments of the Andean region are developing different strategies to reduce deforestation and open BB. For example, Ecuador, within the *Plan Nacional del Buen Vivir*, is supporting a national program entitled *Socio Bosque*. This program transfers direct economic incentives to rural families and local and indigenous communities that voluntarily commit to comply with clearly agreed upon conservation activities. Program goals suggest that 40–50% of incentives may be used for basic needs, while the remaining is targeted for forest control, good practices, fire control management, and reforestation of degraded areas [*de Koning et al.*, 2011]. These plans to reduce deforestation are relevant for reducing BC emissions through a decrease in forest fires [*MAE*, 2012]. Colombia, Ecuador, and Peru are also exploring the Reducing Emissions from Deforestation and Forest Degradation for Sustainable Development (REDD+) as part of their mitigation plans in the near future. Several countries have also implemented alternative approaches to open agricultural burning, including the no-till technique [*Derpsch and Friedrich*, 2009].

5. Key Measurements to Address BC Impacts on the Cryosphere

5.1. Measurements of Snowpack Extent, Glacier Mass Balance, and Streamflow

As discussed in Section 3, ample in situ measurements document the decreasing trends observed in tropical and extra-tropical glaciers. Such studies of glacial mass balance are needed in many more individual glaciers to document trends along the full extent of the cryosphere in the Andes. In this context, a systematic analysis of high-resolution satellite images would be very useful to obtain a more comprehensive picture of the trends as a function of latitude [*Foster et al.*, 2009; *DGA-CECS*, 2011; *Zazulie*, 2015].

Masiokas et al. [2006] studied snowpack and runoff records from 1951 to 2005 and observed that there was a strong correlation between the maximum snow-water equivalent data and river discharge on both sides of the central Andes. Their analysis indicated that even though the records showed an average increase in temperature at all the mountain stations, there has actually been an average increase in snow accumulation in the last 20 years, likely influenced by the increased frequency and intensity of the warm phases of El Niño Southern Oscillation (ENSO). This increased snow accumulation, however, has not slowed the melting of the glaciers, which has been mainly caused by increasing temperatures. In addition, warmer temperatures will likely increase the frequency of liquid precipitation rather than snow, thus accelerating the ablation of snow and ice. Many of the stations used in this study have been discontinued, losing valuable time series that allow the evaluation of trends. An effort should be made to re-start those closed stations and to also establish new stations, particularly at high altitude in regions of sensitive water availability.

River discharge records from mountainous headwaters, however, offer a less clear-cut picture. *Cortés et al.* [2011] analyzed hydrograph timing and other river flow characteristics in rivers flowing on the western side of the Andes Cordillera between 30°S and 40°S and found no statistically significant trends over the 1961–2006 period for those rivers more strongly dependent on snow and glacier melt. However, rivers flowing from lower elevation headwaters displayed trends most likely associated with spring and summer precipitation decrease. *Rubio-Álvarez and McPhee* [2010] also analyzed trends and cyclical components in rivers between 35°S and 42°S, finding no trends except for summer flows in rainfall-dominated streams. *Casassa et al.* [2009] studied annual and end of summer (February) run-off trends for 13 river gauge stations in central–south Chile between 27°S and 47°S, which showed a predominance of positive February trends within the period 1950–2007, although not statistically significant.

5.2. Measurements of Water Quality

Water quality changes can occur with glacial retreat. *Fortner et al.* [2011] showed that newly exposed sulfide-rich rock outcroppings likely led to water quality degradation in a sulfide-rich valley in the Cordillera Blanca, Peru. High levels of sulfides likely led to increased dissolved metal concentrations (Fe, Al, Mn, Zn, Pb, Ni, Co, and Cu) and decreased pH values significantly reducing water quality. Additionally, glacial melt water reduction due to glacier loss could deplete wetlands and shallow ground water, which could increase oxidation and enhance the release of toxic elements, further degrading water quality. In sulfate-rich regions, dissolved metals should be monitored regularly to determine if there are changes over time.

5.3. Measurements of Meteorological Parameters

Temporal and spatial distributions of the meteorological parameters and solar and terrestrial radiative fluxes are required in order to understand the trends in the extent of the Andean cryosphere. A number of studies have examined temperature and precipitation trends using gridded in situ observations, reanalysis data, and global climate models (GCMs). For example, *Bradley* [2004] examined the temperature projections by seven GCMs using a scenario that assumed a doubling of CO^2, showing an increase in the average temperature of $>2.5°C$ over the entire length of the Cordillera, from Peru to Chile, with the highest elevations experiencing the largest increases.

Falvey and Garreaud [2009] found an average surface cooling along the Chilean coast between 1979 and 2006 but warming (+0.25°C/decade) 100–200 km inland, in the mountain regions. These results were extended by *Vuille et al.* [2015] who found that the warming above 1000 m a.s.l. has occurred at least since 1960, with no interruption during the mid-1970s, and along the western slope of the tropical and subtropical Andes. *Garreaud* [2013] presents changes in the zero-isotherm along central Chile. *Zazulie* [2015], validating reanalysis with gridded in situ data, shows only significant trends in temperature at high altitudes between 30°S and 37°S but no significant trend in the 0°C-isotherm. *Rusticucci et al.* [2014] show that although no significant trends in average winter precipitation over the entire region were found, precipitation had decreased on the west side of the Andes and increased on the east side, i.e., there has been a shift in the precipitation pattern but not in the average intensity between 1961 and 2010. Trends in precipitation between 2050 and 2100 show large variability between the high-resolution coupled GMCs, with a decrease in the ensemble average of the tropical Andes and increases in the southern Andes.

Several of the stations used in these studies (and also in studies discussed in Section 2), particularly at high altitude, have been discontinued, requiring careful statistical analysis of the gridded datasets in order to evaluate trends. There is currently a striking paucity of systematic observations along the Andes. For example, there are only a few hundred surface weather stations in South America, of which approximately 260 are included in the Global Climate Observing System (GCOS) under the World Meteorological Organization (WMO). Only about 30 of them are relevant for the Andean region, and there are only six radiosonde stations, all located on the western side of the Cordillera. Approximately 100 precipitation gauges are installed along the 7000 km mountain range. Figure 6 summarizes measurements currently available in South America. These sites are operated mainly by weather services and some by academic institutions. There is a clear need to make a concerted effort to build up a network of high-altitude stations to continue to document the trends in meteorological conditions affecting cryosphere evolution.

5.4. Measurements of BC and Dust Deposits onto Snowpack and Glaciers

Mineral dust and BC on the surface and mixed with snow and ice can contribute to its melting and sublimation. Several ice core and firn analyses clearly show the presence of anthropogenic tracers on the high Andes [*Bolius et al.*, 2006; *Eichler et al.*, 2015]. However, the potential impact of BC on the Andes snowpack and glaciers has been explored only sporadically by means of measurements [*Cereceda-Balic et al.*, 2012; *Jenk et al.*, 2013; *Schmitt et al.*, 2015], precluding identifying the relative importance of BC and dust in explaining the accelerated retreat of snow and glaciers along the Andes.

There are two pathways by which BC and dust can affect the surface of snow and ice: directly by dry deposition or indirectly by wet deposition. In dry deposition, the particles can contact the surface as a result of sedimentation (gravitational settling) aided by small-scale turbulent eddies. Snow allows wind gusts to penetrate it to some depth and thus greatly enhances dry deposition [*Heintzenberg and Rummukainen*, 1993; *Harder et al.*, 1996]. Measuring dry deposition is not straightforward, and available methods involve eddy covariance techniques [*Pryor et al.*, 2007], which in turn require fast measurements of particle concentration and vertical wind velocity that are difficult to obtain continuously under the harsh weather conditions prevalent in winter in the Andes.

Some of the aerosol particles may be scavenged through activation and collisions in clouds and participate in the development of the precipitation. Wet deposition of particles during rain and snowfall can be sampled by standardized equipment. However, there are currently only a couple of sites sampling precipitation

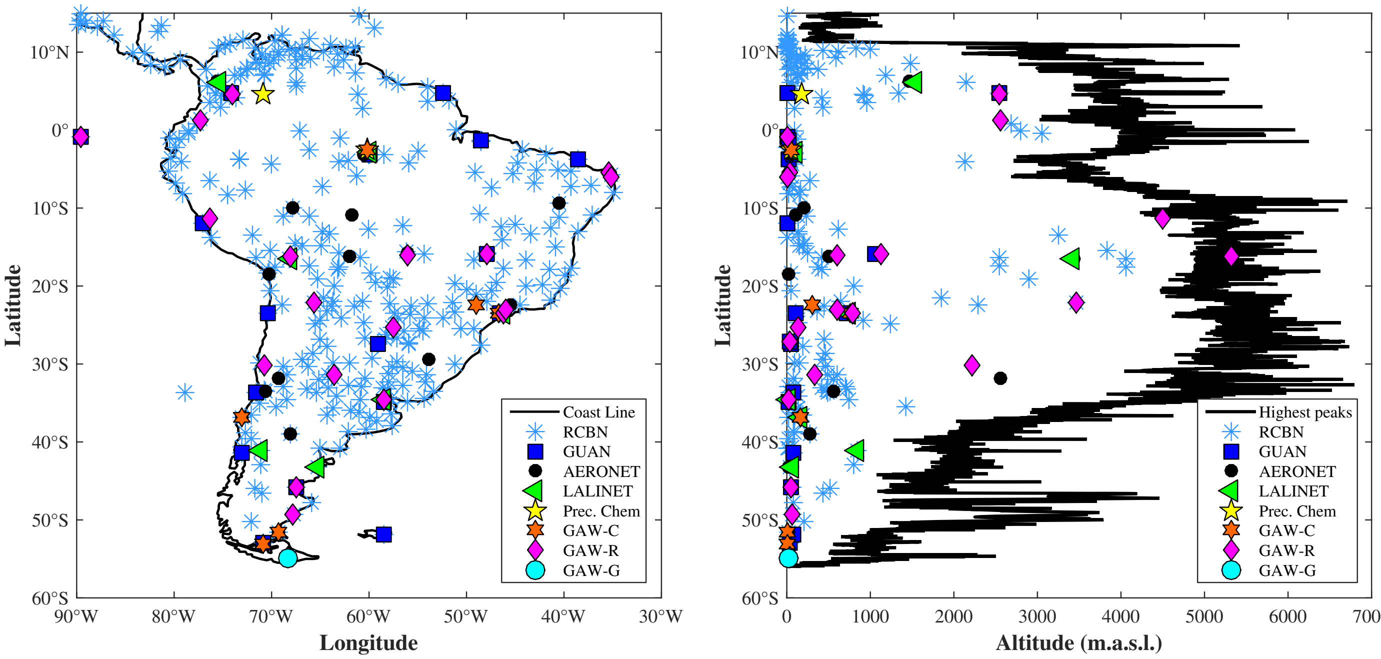

Figure 6. Locations of monitoring sites in South America. The networks correspond to the Regional Basic Climatological Network (RBCN), the Global Upper Air Network (GUAN), the **AE**rosol **RO**botic **NET**work (AERONET), the Latin America Lidar Network (LALINET) as well as the Global Atmospheric Watch (GAW) as in year 2014. GAW comprises contributing (GAW-C), regional (GAW-R), and global (GAW-G) stations. The left panel shows their horizontal distribution, and the right panel shows the corresponding latitudes and altitudes for Andean stations (between 60°W and 80°W).

chemistry on a regular basis in South America, none along the Andes [*Vet et al.*, 2014]. The implementation of a network of wet deposition sites at high altitude could contribute information to determine the extent of the contribution of deposited particles on water composition and quality.

McConnell et al. [2007] and *Schwarz et al.* [2012] determined the mass concentration of refractory BC (rBC) in liquid water, snow, and ice cores with the Single Particle Soot Photometer (SP2). Schwarz *et al.* [2013] provide some evidence that the determination of the size distribution of BC in snow may reveal information about the removal processes depositing the BC and the snow temperature history.

The Integrating Sandwich spectrophotometer (ISSW) [*Grenfell et al.*, 2011] technique has been used in various forms for decades. This technique uses light transmission through filters loaded with particles to determine the spectral absorption. Using this technique, it is possible to quantify both dust and BC, although uncertainties increase with higher dust concentrations [*Schwarz et al.*, 2012].

Less specific techniques can be used to analyze the light-absorbing properties of particles in snow, such as the Light-Absorbing Heating Method (LAHM) to determine relative concentrations. *Schmitt et al.* [2015] report results from snow samples collected by the American Climber Science Program (ACSP) for 3 years in the Cordillera Blanca Mountains of Peru. Clear evidence of BC/dust is shown in samples from glaciers upslope of the city of Huaraz, while much lower concentrations were seen in glaciers at the end of pristine valleys.

Only a few intercomparison studies have been completed and more would be valuable. *Schwarz et al.* [2012] showed results of an intercomparison study between the SP2 and the ISSW, and *Schmitt et al.* [2015] showed comparisons of a small dataset of LAHM and SP2 results. An intercomparison study between the three techniques would be very valuable as they vary substantially in cost and complexity.

5.5. Measurements of Ambient BC and Dust at High Altitude

The Global Atmospheric Watch (GAW) network only has one high-altitude site in South America: Chacaltaya near La Paz, Bolivia, the highest station in the world (5240 m.a.s.l). Clearly, this is inadequate to monitor local and regional pollution that may be transported up to the Andean cryosphere. Additional suitable sites should be identified to track changes in aerosol and trace gas properties over the entire length of the Cordillera. PISAC envisages collaborating with WMO in establishing sites at elevations that are relevant for cryospheric observations as part of the network of precipitation gauges in the Americas co-ordinated by GCOS. It is of particular importance to monitor ambient concentrations of BC, BrC, and mineral dust, all of which absorb solar radiation. There are a number of methods for measuring the aerosol absorption coefficients, e.g., filter-based techniques [*Lin et al.*, 1973], photo acoustic absorption spectrometry [*Arnott*, 2003], cavity ring down [*Strawa et al.*, 2003; *Thompson et al.*, 2003; *Pettersson et al.*, 2004; *Baynard et al.*, 2007], or cavity attenuated phase shift spectroscopy (CAPS) [*Massoli et al.*, 2010]. More on these techniques can be found in *Bond and Bergstrom* [2006] and *Lack et al.* [2014]. The light scattering coefficient can be measured by nephelometers [*Heintzenberg and Charlson*, 1996]. The SP2 quantifies the mass of refractory BC (rBC) in individual particles, and experimentally, rBC is equivalent to elemental carbon (EC) measured correctly with thermo-optical techniques [*Kondo et al.*, 2011].

5.6. Measurements of Air Quality in Cities and Transport to the Andes

The high Andes are the seat of a number of medium-size to large cities whose emissions can potentially reach some of the mountain glaciers located in the region. The same applies to the abundant open burning sources of particles and gases in South America, as seen in Section 4.

Air quality networks exist in several urban centers including Santiago, Lima, Quito, and Bogota [*Zhu et al.*, 2013]. These networks collect criteria pollutants including particulate matter; however, speciation and size distribution studies and characterizations of aerosol optical properties are made only sporadically [e.g., *Brito et al.*, 2013].

BC as well as elemental and OC are measured using aethalometers and thermal analysis in some of these networks [*Seguel et al.*, 2009; *Backman et al.*, 2012]. This may change in the future as health impacts of BC have been highlighted [*Janssen et al.*, 2011; *Jacobson et al.*, 2014]. Moreover, measurements of BC concentration have been suggested as a more appropriate metric than particulate matter to assess the impact of transport policies on air quality [*Invernizzi et al.*, 2011; *Reche et al.*, 2011].

Assessing the impacts of air pollution in the mountains downwind from cities and rural areas will require characterization of the vertical distribution of gases and aerosols, which depend on boundary layer processes and mesoscale circulations. These processes are seldom monitored on a regular basis, and so far, few field measurement campaigns have been carried out [e.g., *Seguel et al.*, 2013].

Satellite-borne instruments provide potentially useful information [*Cardozo et al.*, 2011]; however, the sharp gradients and reflectivity of the Andes pose particular challenges for remote sensing [e.g., *Escribano et al.*, 2014]. Moreover, satellite retrievals are partially hampered by the presence of the Southern Atlantic Anomaly, which leads to a high noise to signal ratio. Recent algorithms provide more accurate estimates of aerosol optical depth from satellite platforms; however, they are computationally intensive and not available on an operational basis [*Hu et al.*, 2014]. Detecting BC from space appears unfeasible for retrieval techniques [*Warren*, 2013]. There are currently no methods for deriving the ambient concentration of BC using passive remote sensing techniques from ground-based or space-borne sensors. A brief review of some of the approaches that are being taken to estimate effective BC (eBC) is found in *Lack et al.* [2014].

5.7. Intensive Field Campaigns at High Altitude

The presented review of observations and modeling studies and results from other mountain regions (e.g., Alps and Himalayas) provide sufficient evidence to support the development of intensive measuring campaigns to better quantify the underlying processes and to untangle the impacts of BC and dust on the Andean cryosphere. The primary challenge is to find accessible measurement sites, with electricity, and near snowfields and glaciers that have experienced melting and sublimation in the past 50 years. Lacking such a location, the measurement site downwind of the source of emissions should be situated at as high of an elevation as possible.

A first, such an exploratory campaign was carried out 65 km SE of Santiago, Chile, in a narrow canyon (Maipo) at an elevation of 1500 m during the transition from austral winter to spring. The project Pollution Impact on Snow in the Cordillera - Experiments and Simulations (PISCES) took place in September and October 2014 to test the hypothesis that particulate pollution from the boundary layer over Santiago could be sampled at the research site on its way to the snowpack and glaciers located at the high end of the canyon where it could be deposited and, thus, could change their albedo. A set of instrumentation to determine, among others, in situ optical properties of particles to derive BC concentrations was installed at the site and operated continuously 24 h per day for 5 weeks. The analysis of the observations and the high-resolution regional mesoscale modeling indicate the presence of a shallow valley-mountain circulation, most evident during cloudless days [*Córdova et al.*, 2015]. However, this mesoscale circulation did not reach the elevation of the research site on cloudy days. While a diurnal cycle on cloudless days was observed for ultrafine particles, no clear evidence was observed of transported BC or particle-bound polycyclic aromatic hydrocarbons, characteristic of urban pollution dominated by diesel-fueled vehicular emissions. Unfortunately, during the 5-week field campaign, only two synoptic events left traces of precipitation at the research site, and no permanent snow was collected; such information was considered essential to evaluate the hypothesis of the wet deposition of particle pollution from Santiago onto fresh snow by frontal systems, which remains to be tested in the future.

6. Conclusion

There is no doubt that the Andean cryosphere is changing rapidly as snowfields and glaciers generally recede, leading to changes in stream flow and water quality along the Andes. The challenge is to identify the principal causes of this change so that action can be taken to mitigate this negative trend. Atmospheric warming and changes in precipitation patterns due to internal climate variability and anthropogenic forcing are considered the main drivers of these changes. Nevertheless, a few modeling and observational studies have indicated the presence of BC and other impurities in the high Andes, with potentially significant impacts on the Andean cryosphere. There is currently a striking paucity of systematic observations along the Andes that precludes a definite conclusion in this respect.

The serious lack of observations, at sufficient spatial and temporal scales, of the physical and chemical state of the atmosphere and the cryosphere is an obstacle that must be addressed to understand the underlying processes that drive glacier changes. Short- and long-term measurement programs, complemented by high-resolution modeling studies, will be required to assert the relative importance of BC deposition and other darkening material, and dynamical forcers. This, in turn, is essential for providing the information leading to effective strategies that can slow or even reverse the current trends in snow and glacial melting that have serious implications for future water supplies for the Andean population.

The apparent disconnect between glacier retreat and water resource trends is one of the key research questions that needs to be addressed if appropriate public policy is to be implemented in order to alleviate the effects of climate change. Several avenues of research are required in order to better address this challenge, including: (a) transitioning from documenting glacier volume changes to predicting ice mass evolution through physically based models; (b) continue the expansion of observational networks (glaciological and climatic) such as those currently being developed by authorities and research centers in Chile and other countries of the region; (c) continue and deepen our understanding of snow redistribution processes, which apparently contribute disproportionately to glacier mass balance; and (d) explicitly assess uncertainty stemming from GCM, downscaling, and modeling errors in water resource predictions under climate change scenarios [*Pellicciotti et al.*, 2014].

Glacier retreat impacts on water resources and ecosystem services are likely to result in high economic and social costs given that institutional arrangements are usually built around dry season flows, which are the most likely to be impacted by cryospheric changes. *Vergara et al.* [2007] estimated that the city of Quito, for example, would have to invest an additional US$100 million in water supply infrastructure due to the disappearance of flows stemming from the Cotopaxi and Antizana glaciers. In Peru, the loss of stream flow would impact hydroelectric power generation with annual incremental costs to the power sector between US$212 million and US$1.5 billion (the higher value associated to rationing in a scenario without gradual adaptation measures). Additional thermal-based generating capacity would have to be implemented, not only increasing the country's carbon footprint but also resulting in higher costs to end users. The cost spread in the latter example highlights the relevance of adaptation studies based on robust scientific knowledge sustained on reliable and consistent observations of glaciated hydrological systems. Realistic modeling of glacier behavior should be the cornerstone of this policy-oriented research, and uncertainty estimation should also be given a relevant role for decision making.

Concerns about detrimental health effects of atmospheric pollutants have led governments in the region to implement policies to attain air quality and emission standards and to reduce deforestation and open BB. Some of the policy measures are relevant for reducing BC and other SLCPs, e.g., "green" taxes for diesel cars, improved stoves, and brick kilns, diesel filters in buses, restriction on open burning, etc., which can also provide mitigation for the potential of BC deposition on the Andean cryosphere. However, such measures are not widely implemented in the region. There is a need to streamline a set of emission control measures for each country, taking into consideration unique political, institutional, cultural, and socioeconomic circumstances and based on a sound scientific foundation.

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