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Contribution of biomass burning to black carbon deposition on Andean glaciers: consequences for radiative forcing

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Abstract

Andean glaciers have melted rapidly since the 1960s. While some melting is likely due to anthropogenic climate change driven by increasing greenhouse gases, deposition of light-absorbing particles such as black carbon (BC) may also play a role. We hypothesize that BC from fires in the Amazon Basin and elsewhere may be deposited on Andean glaciers, reducing the surface albedo and inducing further melting. Here we investigate the role of BC deposition on albedo changes in the Andes for 2014–2019 by combining atmospheric chemistry modeling with observations of BC in snow or ice at four mountain sites in Peru (Quelccaya, Huascarán, Yanapaccha, and Shallap) and at one site in Bolivia (Illimani). We find that annual mean ice BC concentrations simulated by the chemical transport model GEOS-Chem for 2014–2019 are roughly consistent with those observed at the site with the longest record, Huascarán, with overestimates of 15%–40%. Smoke from fires account for 20%–70% of total wet and dry deposition fluxes, depending on the site. The rest of BC deposited comes from fossil fuel combustion. Using a snow albedo model, we find that the annual mean radiative forcing from the deposition of smoke BC alone on snow ranges from +0.1 to +3.2 W m^{-2} under clear-sky conditions, with corresponding average albedo reductions of 0.04%–1.1%. These ranges are dependent on site and snow grain size. This result implies a potentially significant climate impact of biomass burning in the Amazon on radiative forcing in the Andes.

1. Introduction

The number of fires in the Amazon has increased since 2013, with the number of active fires in 2019 alone three times higher than in 2018 (Barlow *et al* 2019). Smoke from the Amazonian fires can affect regional climate through interaction with incoming sunlight or clouds (Procopio *et al* 2004, Ramathan and Carmichael 2008, Bond *et al* 2013, Sena *et al* 2013, Liu *et al* 2020a). For example, black carbon (BC), a major component of smoke, absorbs solar radiation and potentially stabilizes the atmosphere, leading to decreased convection and precipitation (Tosca *et al* 2010, Liu *et al* 2020a). Recent studies have also suggested that BC from the Amazon fires may be transported to the Andes and deposited on snow or ice, reducing the surface albedo and leading to melting (Molina *et al* 2015, Schmitt *et al* 2015). However, the influence of smoke BC—i.e. the BC emitted by fire activity—on tropical glaciers in the Andes has not been well quantified. In this study, we use BC observations in Peruvian and Bolivian snowpack and glaciers together with models of chemical transport and radiative forcing to examine the impact of smoke BC deposition on surface albedo across the Andes.

In the Peruvian Andes, as much as one-half the glacial surface area has been lost since the mid-20th century (López-Moreno *et al* 2014, INAIGEM 2018). While some studies have linked significant melting in the Andes to warm periods associated with El Niño (Maussion *et al* 2015; Vuille *et al* 2008a), other studies have traced at least some of the rapid melting to a regional temperature increase of ∼0.1 °C since the 1950s (López-Moreno *et al* 2014, Rabatel *et al* 2013; Vuille *et al* 2008b). In the 21st century, those glaciers with smaller areal extent (<10 km^2) and at altitudes lower than 5400 m above sea level (m.a.s.l.) appear to be the most vulnerable to shrinkage and thinning (Rabatel *et al* 2013). Although the 2010–2020 decline in snow coverage in Chile can be traced to drought (Shaw *et al* 2021), current research does not implicate a long-term decrease in precipitation or snowfall in the disappearance of the Andean glaciers (Vuille *et al* 2018).

A key question is to what extent BC deposition on snow may also affect glacial melting in South America. Previous model studies focusing on the Himalayas and the Arctic have shown that BC deposition on snow may change the regional albedo (Flanner *et al* 2009, Lee *et al* 2017). These studies suggested that BC from fossil-fuel combustion or biomass burning may be transported to these remote locations, enhancing the solar radiation absorbed by the surface snow or ice. Other light-absorbing aerosols such as dust can also have this effect (Flanner *et al* 2009, Kaspari *et al* 2014, Skiles *et al* 2018). By increasing surface heating, the accumulation of these light absorbing aerosols on snow may contribute to melting and increased runoff of glaciers (Hansen and Nazarenko 2004, Xu *et al* 2009). Evidence of these processes in the Andes has begun to appear. Khan *et al* (2017) found that even pristine snow in remote glaciers in Chile has been contaminated with BC, but sources of this BC were unknown. Using observations from the Moderate Resolution Imaging Spectroradiometer (MODIS), an instrument aboard the Terra and Aqua satellites, Malmros *et al* (2018) found a ∼13.4% decrease in snow cover extent and a mean ∼7.4% decrease in snow albedo from 2000 to 2016 for Andean glaciers in Argentina and Chile.

Satellite observations over South America show that smoke plumes from Amazon fires during the dry season can travel thousands of kilometers, even over the Andes (Bourgeois *et al* 2015). The space-borne sensor Cloud Aerosol LIdar with Orthogonal Polarization has detected smoke plumes at elevations as high as 5 km above sea level in the Andes (de Magalhães Neto *et al* 2019), consistent with reports of smoke plumes stagnating and circulating in the foothills of Bolivia (Jury and Pabón 2021). Recent AERONET measurements at the Huancayo Observatory, Peru, found that aerosols from both urban sources and biomass burning during the Amazonian dry season (mid-July to mid-October) contributed to the aerosol optical depth (AOD) at this Andean site (Estevan *et al* 2019). Using a Lagrangian plume model and a snow/ice mass balance model, de Magalhães Neto *et al* (2019) estimated that smoke BC deposition at the Zongo Glacier in Bolivia was responsible for ∼3% of the melting in 2010, with higher melting rates possible in the presence of dust. Across the region, smoke BC may come from fires in the Amazon Basin as well as from local agricultural fires.

This study determines the extent to which deposition of BC particles on snow can affect the albedo and surface energy balance of selected Andean glaciers. We are especially interested in the impacts of BC emitted by local and regional fires on these glaciers. Here we use measurements of BC in snow and ice together with two models—GEOS-Chem, a 3D global atmospheric chemistry and transport model, and SNow, ICe, and Aerosol Radiative (SNICAR), a snow albedo model—to study the impact of smoke from fires on Andean glaciers. Using these methods, we can estimate radiative forcing from BC concentration on glacial snow and the proportion of radiative forcing from biomass burning. Although the BC measurements are sparse and radiative forcing is a relatively rough metric of climate impacts, our study nonetheless builds on past work that compared the variability of BC deposition in Andean ice cores to fire trends across South America (e.g. Osmont *et al* 2019). We extend the work of de Magalhães Neto *et al* (2019) by investigating the impacts of BC deposition from both fossil-fuel and fire sources over the entire Peruvian and Bolivian Andean region over five years. Given the recent uptick of fires in South America and the lengthening of the dry season (Fu *et al* 2013, Agudelo *et al* 2019), our results could have implications for ecological and human health in the region. For example, the continued loss of Andean glaciers would affect the many communities that rely on dry season runoff for agriculture, drinking water, and hydro power, and could also lead to a higher frequency of avalanches and overflowing glacial lakes (Molina *et al* 2015).

2. Data and methods

2.1. In-situ observations of BC and light-absorbing particles in snow and ice

For observed BC deposition fluxes in Peru, we rely on BC concentration measured throughout the uppermost layers of an ice core retrieved in August 2019 at the summit of Huascarán (6768 m.a.s.l.), and in snow pit samples collected in 2016 and 2018 at the summit of the Quelccaya ice cap (5670 m.a.s.l.). Annual mean BC concentrations are measured by laser induced incandescence using a Single Particle Soot Photometer (SP2), as described by Sierra-Hernández *et al* (2022) and Barker *et al* (2021) for five thermal years at Huascarán and two thermal years at Quelccaya, where the thermal year is defined as the interval from one Amazonian dry season in the Andes to the next. The mean BC concentration for the five years in Huascarán ice core is 4.7 ± 4.9 ppb, and at Quelccaya the average BC concentration in the snow pits is 3.2 ± 2.5 ppb. The dating of the Huascarán ice core is based on counting of the annual cycles in δ^{18}O, dust, and other chemical constituents, which are well preserved at the top of the core (Thompson *et al* 2017). In Bolivia, we rely on observations of BC deposition in the ice core at Illimani (6438 m.a.s.l). Measurements here are also carried out by SP2, and BC is specified as refractory BC, as described in Lim *et al* (2014).

In addition, we analyze monthly deposition fluxes of light-absorbing particles, also known as effective BC (eBC), at Yanapaccha and Shallap, two glaciers in the Peruvian Andes located ∼60 km apart at 5460 m.a.s.l., and 5680 m.a.s.l., respectively. The eBC concentrations are analyzed following the light absorbing heating method (LAHM), a technique that measures the ability of particles on filters to absorb visible light (Schmitt *et al* 2015, 2022). Although this method cannot differentiate between different light-absorbing particles such as BC or dust, it is calibrated with a BC standard. More information on the LAHM can be found in supplementary section S1.

To best compare the observed and modeled concentrations of BC and eBC in snow, we rely on observed precipitation. Figure 1 shows the locations of the BC and eBC collection sites as well as the observation sites for precipitation.

2.2. AOD

To help validate the model, we use daily mean observations of AOD at 500 nm from 51 ground-based sites in the AErosol RObotic NETwork (AERONET, v2, level 3); https://aeronet.gsfc.nasa.gov/), distributed across South America. The comparison is discussed in supplementary section S2.

2.3. GEOS-Chem

We use GEOS-Chem v.12.8.1 (DOI: https://doi.org/10.5281/zenodo.3837666), a 3D global atmospheric chemical transport model, driven by assimilated meteorological fields from the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2; Gelaro *et al* 2017, https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). We perform two sets of six-year nested grid simulations, with and without fire emissions, at 0.5° × 0.625° spatial resolution for 2014–2019 for South America. The nested grid simulations spans from 15° N to 60° S and 30° W to 85° W. Boundary conditions are taken from two global tropospheric simulations, also with and without fire emissions, at a spatial resolution of 2° × 2.5° and 47 vertical levels for the same years. For global and regional biomass burning, we rely on the Global Fire Emissions Database version 4 with small fires (GFED4.1 s; Giglio *et al* 2013, van der Werf *et al* 2017). This inventory relies on active fire observations to estimate emissions from small fires, but still may miss short-lived fires, especially in rough terrain (Liu *et al* 2020b). For anthropogenic emissions, we use the inventory of the Community Emissions Data System (CEDS; Hoesly *et al* 2018). The supplementary section S3 provides more detail on GEOS-Chem.

Some previous versions of GEOS-Chem overestimated BC concentrations in remote regions. For example, Wang *et al* (2014) found that there was a bias toward high concentrations of atmospheric BC in GEOS-Chem relative to observations from the High-Performance Instrumented Airborne Platform Pole-to-Pole Observations (HIPPO) campaign. GEOS-Chem also overestimated observed BC in the Atmospheric Tomography Missions (ATom) campaign (Schill *et al* 2020). However, recent updates to the rainout efficiencies in version 12.6.0 have reduced biases of BC concentrations in the Arctic (Luo *et al* 2020), and the BC overestimate in Schill *et al* (2020) can be traced to the application of biomass burning emissions from the Quick Fire Emissions Dataset, which tends to be biased high (Liu *et al* 2020b). GEOS-Chem has successfully reproduced BC deposition on snow in Antarctica and in the Bolivian Andes (Liu *et al* 2021). Tuccella *et al* (2021) found that GEOS-Chem can capture the regional variability of BC concentrations in snow in the Northern Hemisphere and Antarctica for a 5 year period.

2.4. Methods for calculating modeled BC concentration in snow and ice

To compare the modeled BC wet deposition fluxes to observations, we need to consider the high elevations of the glaciers and the biases in MERRA-2 precipitation. To that end, we normalize the modeled wet deposition with observed rates of precipitation. Calculation of dry deposition is more straightforward. To determine the modeled concentrations of BC in snow, we again rely on observed precipitation, as described in supplementary section S4.

2.5. Applying SNICAR-ADv3 to determine the radiative forcing from BC

We use the snow albedo radiative transfer model SNICAR model with the Adding-Doubling solver (SNICAR-AD, version 3; Flanner *et al* 2021) to quantify the radiative impacts of BC. SNICAR has previously been used to quantify BC-snow-albedo effects over the Tibetan Plateau (Kaspari *et al* 2014, He *et al* 2017) and elsewhere (Cereceda-Balic *et al* 2020; de Magalhães Neto *et al* 2019, Flanner *et al* 2009, Kaspari *et al* 2014, Schmitt *et al* 2015). In this study, we apply SNICAR-ADv3 to quantify the radiative forcing due to BC in snow on Andean glaciers. The annual average radiative forcing from BC is calculated for the 2014–2019 period for the five glacier sites presented here (Huascarán, Quelccaya, Yanapaccha, Shallap, and Illimani). We calculate radiative forcing for the three estimates of BC concentrations at each location derived from the three different values of precipitation, as described above. We also isolate the radiative forcing attributable to smoke BC at each site, again applying the three BC concentrations. In the radiative forcing calculation, we do not consider the BC evolution in snowpack and assume that BC is well-mixed throughout the snow column. Such an approach allows us to account for uncertainty in the model snowfall and to estimate the contribution to radiative forcing due to smoke from fires in the Amazon and elsewhere. Details of the SNICAR-ADv3 calculations are described in supplementary Section S5.

3. Results

Figure 1 shows the spatial distribution of the average annual fire counts for 2014–2019, as well as the locations of the BC observation sites in the Andes. Most fires occur in southwestern Brazil, but some take place in the Andes as close as ∼25 km from the observation sites. For the 2014–2019 Amazonian dry season (August- November), GEOS-Chem simulates significant atmospheric BC at the surface centered in the Amazon region (figure S3), and extending across the Bolivian Andes, where concentrations are as large as 0.3 μg m^{-3}. The values across much of the Andes are comparable to those inferred over the Arctic (∼6 mg m^{-2} yr^{-1}, Breider *et al* 2014), where BC has previously been hypothesized to contribute to snow and ice melting.

Modeled BC deposition fluxes at the surface, averaged over 2014–2019, are shown in figure 2. We find that wet deposition is on average three times greater than dry deposition across South America, with most BC dry deposition occurring closer to emissions sources (figure S4). During the Amazonian dry season, wet deposition of BC coincides spatially with some glaciers in the Andes. Sensitivity studies using GEOS-Chem indicate that both anthropogenic and biomass burning emissions contribute to BC deposition at the observation sites in the Andes (figure 2). The relative importance of these sources is regionally dependent, with BC deposition from biomass burning emissions especially significant along the Andes in southern Peru and Bolivia. Convection along the eastern flank of the Andes is responsible for greater BC wet deposition in eastern Peru and Bolivia than in other locations (figure 2). Combustion of fossil fuels has a larger impact on BC deposition near the Pacific coast of Ecuador and Colombia.

Consistent with these results, we find that the contribution of smoke BC to the total BC flux on Quelccaya is double that on Huascarán (42% vs. 20%). Quelccaya is located closer to the fires than Huascarán and at a lower altitude in the Altiplano with flatter geomorphological features and ice caps, making it more likely to experience the easterly winds transporting smoke from fires in the Amazon Basin. Also, the summit of Huascarán at 6768 m.a.s.l., rises above the height of most Amazonian smoke plumes, unlike the lower elevation (5670 m.a.s.l.) of the Quelccaya ice cap.

Figure 3 shows the annual accumulations of BC in snow on Huascarán and Quelccaya in both the observations and the model. Modeled concentrations are determined using estimates of snowfall rates, as described in section 2.3. At Huascarán the modeled BC is roughly consistent with observations, with overestimates of 15%–40% for the 2014–2019 thermal years, within the standard error of the measurements. At Quelccaya, GEOS-Chem overestimates the total BC concentration by 50% in the 2015–2016 thermal year, again within the standard error of the measurements, but by 360% in 2017–2018.

Figure S5 compares observed monthly eBC accumulations in snow at Yanapaccha and Shallap with the modeled snow concentrations of BC. We find that the model values of snow BC are only about one-tenth those of the observed eBC at these sites, in part because eBC includes all light-absorbing particles, including dust. In addition, both locations experience melt-freeze cycles regularly, meaning that the light-absorbing particles initially buried in the snow typically end up on the surface. Sublimation and local agricultural burning may also have enhanced the eBC snow concentrations at these sites, processes that GEOS-Chem cannot capture (figure S5). In any event, the figure reveals that fossil fuels emissions contribute similarly to the BC deposition fluxes at Yanapaccha and Shallap. The city of Huaraz with a population of ∼140 000 people is close to both locations—roughly 20 km from Shallap and 55 km from Yanapaccha—and a potential source of BC from fossil fuel combustion. We find that fire emissions contribute 18% of the modeled BC snow concentrations at Yanapaccha and 16% at Shallap.

Figure 4 illustrates the modeled annual mean BC concentrations between 2014–2019 in surface snow across the Andes, with the three panels showing results for the three different estimates of snowfall accumulations. GEOS-Chem captures the average snow BC concentrations at Huascarán and Illimani but overestimates the BC concentrations at Quelccaya, as already noted above. We find that fires account for a significant percentage of BC deposition in the Andes. Consistent with the spatial pattern of deposition fluxes (figure 2), figure S6 shows that glaciers on the eastern flank of the Andes are the most affected by smoke BC during the 2014–2019 period, accounting

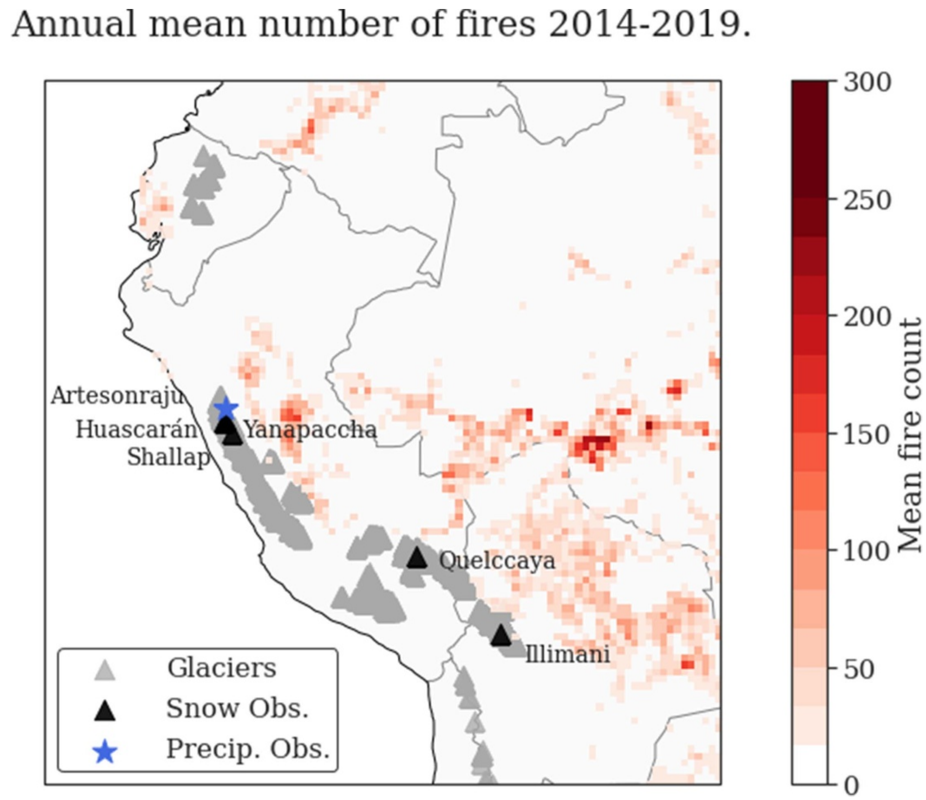

Figure 1. Annual mean number of fires for 2014–2019 in red, aggregated over 0.25° × 0.25° grid cells, as detected by MODIS. Gray triangles denote locations of glaciers from the World Glacier Inventory (https://nsidc.org/data/glacier_inventory/). Black triangles indicate the BC observation sites on glacial snow or ice; Yanapaccha (9.0 °S, 77.6 °W) and Huascarán (9.1 °S, 77.6 °W), which are 15 km apart, are represented by a single black triangle northwest of Shallap (9.5 °S, 77.3 °W) in Peru. Snow observations of BC at Quelccaya (13.9 °S, 70.9 °W), Peru, and Illimani (16.6 °S, 67.8 °W), Bolivia, are also represented with black triangles. Annual precipitation totals are derived from the snow/ice measurements at Huascarán and Quelccaya. The blue star denotes the Artesonraju weather station, which provides additional precipitation data.

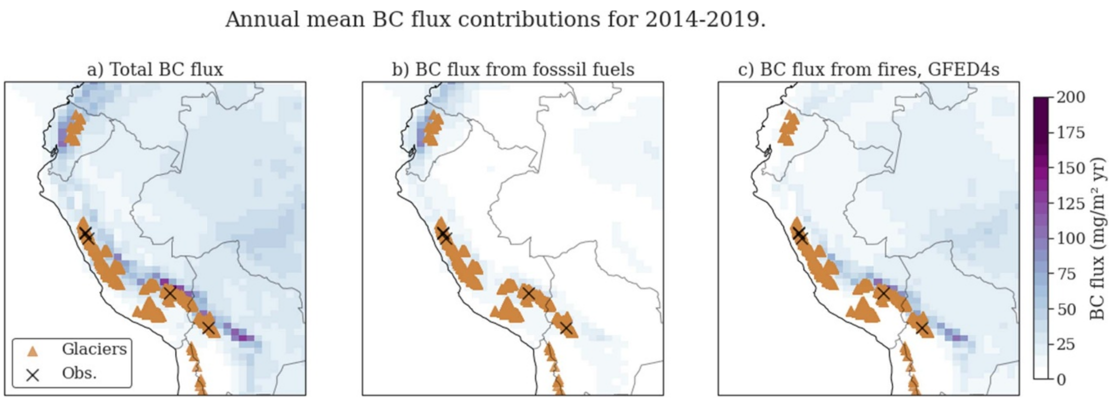

Figure 2. Modeled BC deposition fluxes at the surface, averaged over 2014–2019, in mg m^{-2} yr^{-1}. Fluxes include both wet and dry deposition. Panel (a) shows the total BC flux, panel (b) the contribution to the flux from fossil fuels, and panel (c) the contribution from fires, calculated with the GFED4s emission inventory. Brown triangles represent the locations of glaciers, and black ×'s indicate the BC observation sites.

for 70%–80% of total BC there compared to 20%–30% elsewhere in the Andes.

We use SNICAR to evaluate the radiative role of smoke BC in snow at the five tropical glaciers—Huascarán, Quelccaya, Yanapaccha, Shallap, and Illimani. Figure 5 shows the annual radiative forcings due to BC deposition in freshly fallen and aged snow for these five glaciers, using the three different estimates of snowfall. Under clear-sky conditions at Huascarán, annual radiative forcing from BC

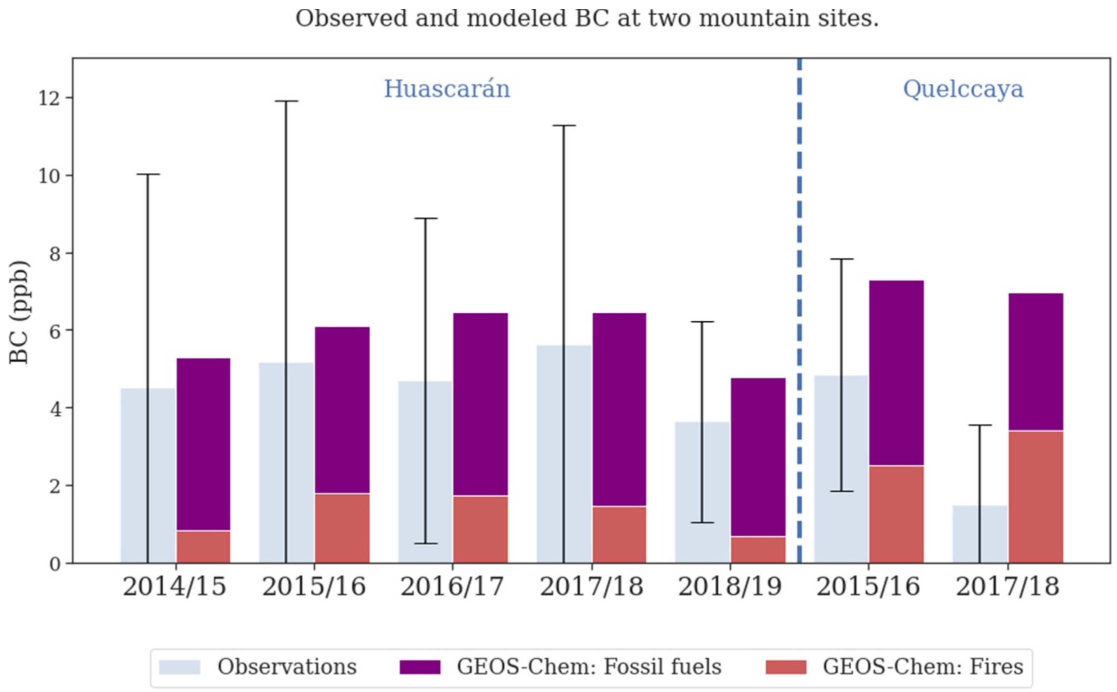

Figure 3. Comparison of observed and modeled BC annual mean concentrations (ppb) in snow on two glaciers in Peru spanning 2014–2019. Observations are shown in light blue for the Huascarán ice core for five thermal years (left) and for the Quelccaya snow pits for two thermal years (right). Black bars indicate the standard deviation of the mean. Modeled BC concentrations are shown as stacked contributions of biomass burning BC in dark red and fossil fuel combustion in purple. Modeled wet deposition fluxes are normalized with observed snowfall accumulation at each location to calculate the modeled BC concentrations shown.

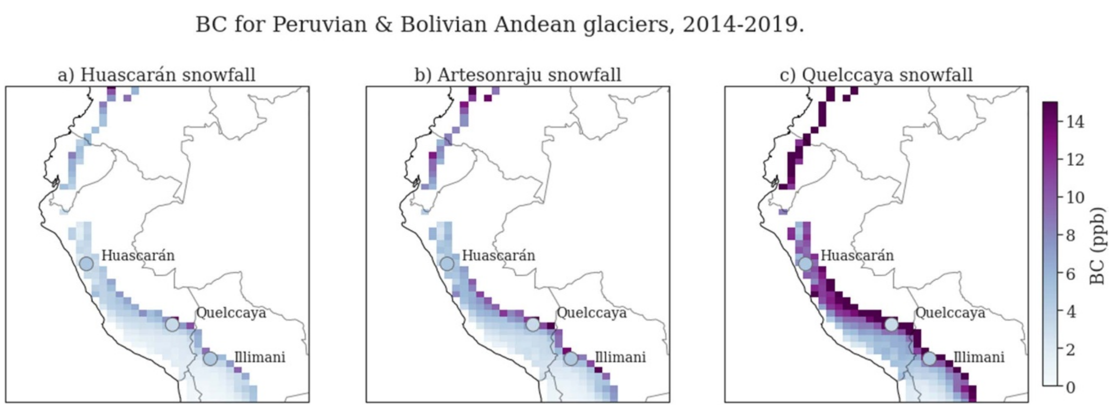

Figure 4. Modeled BC concentrations (ppb) in snow or ice in grid cells above 2000 meters in elevation. Mean BC concentrations (ppb) from observations are indicated by circles for 2014–2019 at Huascarán and Quelccaya and for 2004–2009 at Illimani. Panels show the BC concentrations due to different assumptions of snowfall. Panel (a) assumes yearly snowfall accumulation as determined from the Huascarán ice core, panel (b) from the Artesonraju weather station, and panel (c) from the Quelccaya snow pits. Color bar saturates at 15 ppb. Application of a range of snowfall estimates allows for an assessment of the uncertainty in the modeled values.

deposition ranges from +0.5 to 1.2 W m^{-2} in freshly fallen snow and from +1.5 to +3.6 W m^{-2} in aged snow, relative to a scenario with clean snow, with biomass burning contributing ∼27% of total forcing. In contrast, at Illimani, BC deposition accounts for +0.9 to +2.1 W m^{-2} in recently fallen snow and +2.8 to +6.3 W m^{-2} in older snow, with biomass burning accounting for ∼75% of total forcing. Under cloudy conditions, when less incoming solar radiation is available, these values are relatively the same or slightly lower: +0.4 to +1.1 W m^{-2} in fresh snow and +1.4 to +3.4 W m^{-2} in aged snow at Huascarán and +0.9 to +2.0 W m^{-2} in fresh snow and +2.6 +6.1 W m^{-2} in aged snowed at Illimani (Wiscombe and Warren 1980, Flanner *et al* 2021, Whicker *et al* 2022). The radiative forcings at Yanapaccha and Shallap are similar to those at Huascarán, which is not surprising given their proximity. At Quelccaya, we find the radiative forcings fall midway between those at Huascarán and those at Illimani.

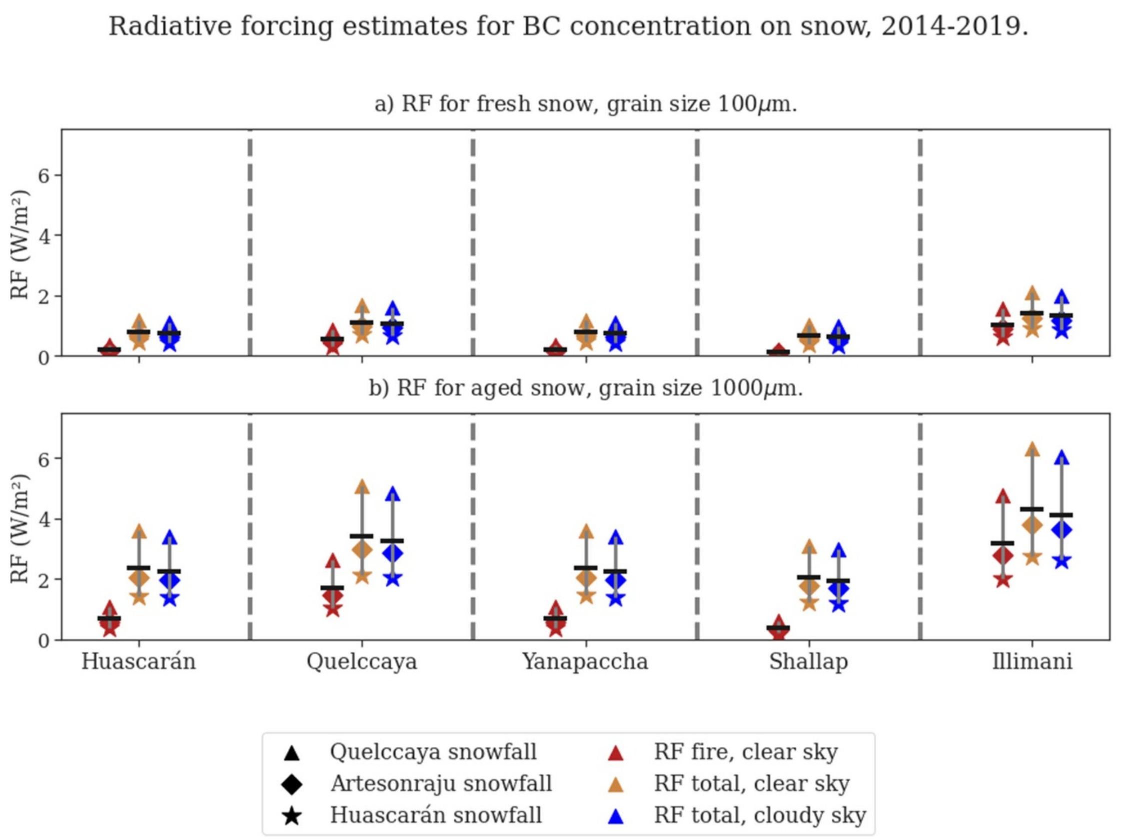

Figure 5. Range of radiative forcing (RF) estimates for BC concentration in snow at five Andean glaciers. Units are W m^{-2}. Panel (a) is for radiative forcing of BC concentrations in freshly fallen snow with grain size of 100 μm, and panel (b) for aged snow with grain size of 1000 μm. The different symbols represent the forcings calculated with different snow accumulations, with stars indicating estimates using snowfall accumulation at Huascarán, diamonds at Artesonraju, and triangles at Quelccaya. Radiative forcing under clear sky conditions is in red for smoke BC (RF fires) and in orange for total BC (RF total), and the forcing under cloudy sky conditions (RF diffuse) for total BC is shown in blue. Gray vertical lines connect the maximum and minimum forcings for each scenario and are meant to facilitate comprehension. The black horizontal bars indicate the mean forcing for each scenario across the different estimates of snowfall accumulation.

4. Discussion

We use a combination of models and observations to investigate the influence of BC from biomass burning on absorbed solar radiation in tropical glaciers in the Andes over the 2014–2019 period. We estimate a range of radiative forcings due to total BC deposition from +0.5 to +2.1 W m^{-2} in fresh snow and +1.5 to +6.3 W m^{-2} in aged snow, under clear-sky conditions at the five glacial sites—Huascarán, Quelccaya, Yanapaccha, and Shallap in Peru, and Illimani in Bolivia (figure 5). During cloudy conditions, radiative forcings due to total BC range from +0.4 W m^{-2} and +2.0 W m^{-2} for fresh snow and +1.4 W m^{-2} and +6.1 W m^{-2} in aged snow across the sites (figure 5).

Our analysis shows that tropical glaciers in southern Peru and in Bolivia are more impacted by BC from biomass burning smoke than elsewhere in the Andes. For example, we find that about 70% of the BC deposited at Illimani, Bolivia, comes from biomass burning emissions, and on clear days smoke BC on average accounts for +1.0 W m^{-2} on recently fallen snow and +3.2 W m^{-2} on aged snow, or about 75% of total BC forcing there (table S1). By comparison, only ~25% of the BC on snow originates from biomass burning in glaciers in the northwestern part of the Andes, such as at Huascarán for these years. The rest of the deposited BC at all sites can be traced to emissions from fossil fuel combustion, possibly from highly populated cities such as Huaraz.

Our results are consistent with previous studies focusing on BC deposition and radiative forcing at Illimani and other remote locations. Ice cores collected at Illimani have revealed an annual average BC concentration of ~1.1 ppb in 1998 (Osmont *et al* 2019) and a peak of 58.3 ppb during the 2007 dry season (de Magalhães Neto *et al* 2019). These observations are comparable to our modeled 2014–2019 average concentrations of 12.4 ppb at Illimani (table S1) and suggest that BC deposition may have increased since the 1990s, consistent with the observed increase in fire activity in the Amazon Basin (Barlow *et al* 2019). In addition, our mean radiative forcing estimates under clear sky conditions of +1.4 to +4.3 W m^{-2} for total BC in fresh or aged snow at Illimani [table S1] are similar to the +1 to +5 W m^{-2} forcings calculated at the Zongo glacier nearby in Bolivia (de Magalhães Neto *et al* 2019).

Similar radiative forcings have been estimated at snow/ice sites in the Himalayas (Ming *et al* 2008), the Arctic (Dang *et al* 2017), and the Swiss Alps (Gabbi *et al* 2015). Our work builds on these earlier studies by analyzing the radiative forcing at multiple Andean sites across five years and by quantifying the contribution of biomass burning to BC deposition at these sites.

There are limitations to our study. GEOS-Chem cannot fully capture the rough topography of the Andes, leading to uncertainty in BC transport and deposition. In locations like Huascarán, the spatial resolution of 0.5° × 0.625° is too coarse to account for the extreme changes in elevation within the grid cell. However, the model elevations are similar to those of the low-altitude glaciers at ∼3–5 km above sea level. Our results are also dependent on the inventories used, both for fire and fossil fuel emissions, whose estimates can vary greatly (Darmenov and da Silva 2015, Liu *et al* 2020b). A newer version of the SNICAR-AD model was recently released, SNICAR-Adv4, which accounts for the optical properties of glacial ice (Whicker *et al* 2022). While using the newer version of the model would likely not change the results of this study appreciably, it could quantify the contribution of BC on bare glacial ice to radiative forcing. Finally, we assume BC concentrations are well-mixed in snowpack.

5. Conclusions

Our results suggest that BC deposition from biomass burning significantly impacts the surface energy balance at tropical glaciers in the Andes. The annual mean forcing of smoke BC on snow ranges from $+0.1$ W m^{-2} to as much as $+3.2$ W m^{-2} under clear sky conditions and considering a range of snowfall estimates (table S1). The corresponding broadband albedo reductions from smoke BC deposition range from 0.04% to 1.1%, temporally averaged (table S2). Follow-up studies could investigate the influence of such large radiative forcings on the melting of snow or ice and could consider the effects of dust deposition. This study also points the way forward to estimating the impact of smoke BC on albedo and regional climate in glaciers across the entire Andes, using a climate model that includes a detailed representation of snow/ice processes. In the recent past (2005–2013), governmental policies in Brazil protected forests and Indigenous lands led to a 70% decrease in deforestation rates and a 64% decrease in the annual number of fires (Barlow *et al* 2019, Nepstad *et al* 2014; https://queimadas.dgi.inpe.br/queimadas/portal-static/estatisticas_paises/). Our study suggests that renewed adherence to these policies in Brazil and implementation of similar policies in Peru and Bolivia could limit the amount of BC being deposited on the Andean glaciers and lessen their risk of disappearing.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/KXVX0J (Mickley and Bonilla 2023).

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Author contributions

All authors contributed equally to the genesis of this manuscript.

Conflict of interest

The authors declare no competing interests.

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