SUPPLEMENTARY MATERIAL EGU25-VIENNA, AUSTRIA

State of the art of black carbon in tropical Andean glaciers

Key definitions of black carbon

What is black carbon (BC)? Black carbon is a type of carbonaceous particle resulting from the incomplete combustion of fossil fuels and biomass. It is characterized by its strong absorption of light in the visible spectrum, making it one of the most potent climate forcers after CO_2. Black carbon is refractory, insoluble in water, and usually occurs as aggregates of sooty spheres. Its dark color allows it to absorb solar radiation and generate local warming in the atmosphere and on the surfaces where it is deposited.

Origin and transport to Andean glaciers: Sources of carbon dioxide (BC) include biomass burning (forest fires, agricultural burning) and fossil fuel combustion (vehicles, industry). In the tropical Andean region, the majority of carbon dioxide (BC) has been identified as originating from vegetation fires (agricultural burning, deforestation), especially in the Amazon and other dry areas, with peaks in the dry season (approximately July to October). Urban emissions also contribute locally: studies in the Cordillera Blanca (Peru) show that glaciers near cities like Huaraz receive a significantly higher BC load than remote glaciers. Once emitted, BC can remain in the atmosphere from hours to several days before being removed by wet (with rain/snow) or dry deposition. This relatively short (but sufficient) atmospheric lifetime allows BC particles to be transported long distances by winds, crossing continents and mountain ranges. In the tropical Andes, atmospheric currents can carry BC from low-lying sources in the Amazon basin to high Andean regions. For example, models in Peru indicate a predominant transport from the north (Ucayali rainforest, Loreto) to the central and southern glaciers during the dry season. In some cases, currents from the Pacific also contribute aerosols (although mainly marine dust or other non-carbonaceous particles).

Black carbon vs. organic carbon and other aerosols: Among the aerosols that darken snow (called light absorbing particles or LAPs), we mainly distinguish:

- **Black carbon (BC):**It is the most absorbent fraction, a product of incomplete combustion. It strongly absorbs broad-spectrum solar radiation and provides positive radiative forcing (warming). It is found mostly in anthropized environments (fuel burning) and can be transported to remote locations before being deposited.

- **Organic carbon (OC):** It encompasses thousands of carbon compounds of organic origin. A subfraction of interest is the so-called brown carbon (BrC), originating from low-temperature combustion and secondary atmospheric reactions. BrC absorbs light in the short-wavelength ultraviolet and visible ranges (especially <700 nm), but less efficiently than BC. It is often co-emitted with BC in fires, also contributing to the darkening of snow.
- **Mineral dust aerosol (MDA):** Particles of soil or desert dust, stirred up by wind or human activities (traffic, mining, agriculture). In the Andes, they can come from local arid zones or even the Sahara in extreme cases, although in tropical glaciers the contribution is local/regional. Dust has a lower absorption capacity than carbon dioxide, but in high concentrations it also reduces albedo. Furthermore, dust can interact with carbon dioxide; for example, dust particles mixed internally with carbon can absorb more light than they do on their own.
- **Others:** Biological aerosols (e.g. snow algae) can also darken snow ("bio-albedo" phenomenon), although in the tropical Andes this topic is little studied.

In short, black carbon is the most significant component of carbonaceous aerosols due to its heat-absorbing capacity. It originates primarily from the burning of biomass and fossil fuels, is transported to great heights and distances, and is deposited in snow along with other particles (organic matter, dust), all of which contribute to the contamination of the cryosphere.

Black carbon cycle in tropical Andean glaciers

Main sources in the tropical Andes: Tropical Andean glaciers receive black carbon from both local and remote sources. Local sources include the burning of nearby grasslands and agricultural fields, mining activities, and vehicle emissions in high-Andean cities. At the regional scale, seasonal burning of forests and savannas in the Amazon and other lowland regions is a dominant source of atmospheric carbon dioxide. Compiled studies indicate that in tropical South America, the majority of carbon dioxide emissions come from open fires linked to agricultural and deforestation activities, with a marked peak between August and October (the dry season in the Southern Hemisphere). For example, in Peru, the number of fires increases dramatically from July onwards, reaching its peak in September (in 2019, the peak was in August due to extraordinary fires). The regions of Ucayali, San Martín, Huánuco, and Loreto in the Peruvian Amazon record the highest amounts of fires and carbon dioxide emissions. These smoke plumes rich in black carbon can be transported towards the mountain range. In addition, contributions from neighboring countries are identified: fires in Bolivia (Chiquitanía, Bolivian Amazon) and Brazil (Acre, Rondônia) also generate plumes that reach the Andes of Peru and Bolivia. On the other hand, urban sources such as highland cities (e.g., Huaraz, La Paz, Quito, Bogotá) contribute local BC that can ascend to nearby glaciers. In the Cordillera Blanca (Peru), glaciers near Huaraz were found to have BC concentrations several times higher than more distant glaciers, evidencing urban influence. In contrast, in very remote glaciers or in sparsely inhabited areas, BC deposition usually comes mainly from the regional atmospheric background, with lower concentrations.

Atmospheric transport mechanisms: Once emitted, BC particles can be lifted by convective currents and transported by meso- and large-scale winds. In the tropical Andes, the dominant circulation during the dry season tends to carry air from the Amazon basin toward the mountain range. Atmospheric models (WRF-Chem) combined with backtrajectories indicate that, for example, the air masses reaching the Huaytapallana glacier (central Peru) during the dry winter come mostly from the north and northeast (lowland rainforest), coinciding with the areas with the largest fires (Ucayali, southern Loreto). These currents transport BC particles to the central and southern Andes. In Bolivia, the Cordillera Real (where Illimani is located) is also influenced by Amazonian fires from northern Bolivia and southern Peru-Brazil. Topographic height plays a role: particles can be deposited before crossing the mountains if monsoon rains remove them, so seasonality is crucial. During the wet season, rainfall washes the atmosphere, reducing the transport of BC; in the dry season, with clear skies, BC persists longer and travels farther. Additionally, local winds (valley-mountain breezes) can transport pollutants from Andean population centers to nearby glaciers on a daily basis. In minor cases, air intrusions from the Pacific with marine aerosols can reach the mountain range, but these aerosols do not contain significant BC.

Deposit on glacial surfaces: Black carbon reaches the surface of glaciers through dry deposition (direct settling of particles by gravity or turbulence) and wet deposition (entrainment by precipitation, such as snow or rain, which then freezes on the glacier). During the Andean dry season, dry deposition typically dominates due to the lack of precipitation: particles gradually accumulate on top of the snow. During the rainy season, wet deposition can introduce black carbon into snowfall, but at the same time, abundant precipitation can bury contaminated layers or even partially clear the surface. Once at the surface, particles can be re-exposed through snow metamorphism: when snow containing impurities melts or sublimates, insoluble particles (such as black carbon and dust) remain on or near the surface. This "resurfacing" process concentrates black carbon in older snow or exposed ice as the dry season progresses. On tropical glaciers, surface melting and nighttime refreezing are common, which can redistribute carbon dioxide (BC) to the upper snow layer. Accumulations of dark sediment are also observed in depressions in the ice called cryoconite pits, where carbon dioxide mixes with dust and organic matter. These cryoconites are sources of heat absorption. In summary, carbon dioxide deposition on glaciers is a continuous process during the dry season (net positive deposition), while during the rainy season, some "cleaning" or vertical redistribution of particles in the snow profile may occur.

Effects on ice dynamics and surface albedo: The most important consequence of the presence of black carbon on snow/ice is a reduction in surface albedo. A lower albedo means the surface reflects less solar radiation and therefore absorbs more heat. The deposited black carbon "blackens" the snow and ice, accelerating their melting. Initially, small amounts of black carbon in fresh snow can have a moderate effect (freshly fallen snow has high reflectivity, and particles can be partially hidden between grains); but as the snow ages and becomes dirty, the impact is amplified. When the snow melts and the underlying glacial ice is exposed, the effect becomes critical, as the ice itself has a lower albedo than clean snow. This feedback is one of the mechanisms by which black carbon contributes to the negative mass balance of glaciers: more absorption -> more melting -> less snow -> more exposed dark surface -> even more absorption, and so on.

Several studies quantify these effects. In the Cordillera Blanca, measurements combined with modeling indicated average albedo reductions of 9% on the Yanapaccha Glacier and 15% on the Shallap Glacier due to accumulated black carbon (2015–2016 values). On the Huaytapallana Glacier (central Andes of Peru), an albedo decrease of between 0.6% and 5% was estimated to be attributable to deposited black carbon, with the largest reductions occurring at the end of the dry season. Although percentages such as 5–15% may seem small, their effect on melting is significant: they translate into increased absorbed energy that accelerates ice ablation. For example, a simulation on the Zongo Glacier (Bolivia) suggests that fire-related black carbon could account for ~3% of the total annual melting in 2010. Furthermore, when black carbon is deposited together with mineral dust, the darkening is exacerbated. In the Zongo simulation, BC only reduced albedo by 1.8–7.2%, but with 1,000 ppm (parts per million) of dust added, the reduction reached

22%, tripling glacial mass loss. This synergistic effect of dust and BC is relevant in the Amazon, where fires emit both types of particles.

Interactions with other climatic and geographical factors: The impact of BC does not act in isolation; it interacts with the local climate and other geographic features:

- **Seasonality and climate:** As mentioned, the highest carbon dioxide loads occur during the dry season, coinciding with maximum solar radiation—precisely when its warming effect is most effective. In years of severe drought, an even lower glacial albedo has been observed, possibly due to increased deposition of dust and soot in the absence of new snow. A study in the Chilean Andes showed decreasing albedo trends linked to periods of drought, implying that, with climate change and less precipitation, glaciers could become dirtier and melt more rapidly.
- **Spatial distribution on the glacier:** Carbon dioxide (CB) is not deposited evenly. It tends to be more abundant near moraines (due to local dust input) and in accumulation areas if it precipitates with snow. Topography also influences this: basins sheltered from the wind may accumulate more carbon dioxide, while steep slopes may be cleared of snow more frequently by avalanches.
- **Interaction with radiation and clouds:** The effect of BC on melting is greatest under clear skies (a lot of sun). Under cloud cover, diffuse radiation slightly reduces the BC's effectiveness in absorbing energy (although the effect is still present). On tropical glaciers, where insolation is intense at high altitudes, BC plays a notable role, especially on sunny days during the dry season.
- **Other pollutants:** As mentioned, mineral dust often coexists with carbon dioxide. In the Sierra Nevada de Santa Marta (Colombia), satellite analyses from 2000 to 2020 showed that dust accounted for 37% of snow albedo variability, while carbon dioxide and carbon dioxide were not statistically correlated. This does not mean that carbon dioxide is not a factor, but rather that at the time scale of observation (monthly), dust was dominant; the influence of carbon dioxide can manifest itself in short-term events following fires that the satellite cannot distinguish well. Likewise, the presence of algae and organic matter on ice can reduce albedo (greenish or reddish patches in snow), an effect documented elsewhere in the world but poorly quantified in the Andes. This could complement the effect of carbon dioxide on some low-altitude glacial surfaces.

In short, black carbon deposited in tropical glaciers acts by reducing albedo and accelerating the melting of snow and ice. Its cycle includes emissions primarily from biomass burning, regional atmospheric transport (favored during the dry season), deposition on the snow surface, and feedback loops that exacerbate glacier mass loss. Along with rising global temperatures, black carbon is a factor explaining the accelerated retreat of many Andean glaciers since the mid-20th century.

Latest scientific findings (last ~5 years)

In recent years, there has been progress in measuring, monitoring, and modeling black carbon in Andean glaciers, as well as case studies in several countries that shed light on its impact:

- **New measurement methods:** Traditionally, BC in snow was measured by filtering melted snow and analyzing the filter. Today, three main approaches are used:
    1. **Filter spectrophotometry (ISSW/LAHM):**measures the absorption of light by particles trapped in a filter to infer equivalent BC concentration. E.g.: Integrating sphere method or optical heating method.
    2. **Thermo-optical analysis:** burns the filter material in stages to quantify elemental carbon (EC = BC) and organic carbon by their different oxidation temperatures.
    3. **Single Particle Incandescence Spectrometry (SP2):**detects refractory BC by measuring the glow of individual particles when heated by a laser. This method provides BC masses with high sensitivity.

  Each method has its pros and cons: ISSW/LAHM give total absorption (BC + dust combined), SP2 gives only pure BC, and thermo-optical distinguishes BC/OC but requires dust corrections. In practice, combined methods are used. For example, in the Cordillera Blanca, samples were analyzed simultaneously with LAHM and SP2; the comparison indicated that in the southern zone (near Huaraz), BC dominates the absorption, while in the northern zone, dust makes a greater contribution. This integration of techniques helps separate the absorption sources.

- **On-site and remote monitoring:**Snow sampling has expanded on various Andean glaciers. Until recently, the majority of data came from the Cordillera Blanca (Peru). Recently, studies have been added in the Cordillera Huaytapallana (central Peru), the Cordillera Vilcabamba (southern Peru), the Sierra Nevada de Santa Marta (Colombia), and ice cores from the Cordillera Real (Bolivia). Remote sensing is also being used: satellite images (Sentinel-2/3, Landsat 8) allow the detection of glacier surface darkening in visible and infrared bands. Although direct satellite detection of BC is difficult, the spectral signature of impurities in the snow can be observed (e.g., dust or algae stain the snow in a detectable way). Global surveys have revealed decreasing albedo trends in recent decades; in the Chilean Andes, Shaw et al. (2021) reported a significant drop in albedo since 2000, linked to dry periods. This suggests an increasing combined effect of dry climate and impurities (possibly carbon dioxide and dust) in the region. In parallel, models such as SNICAR (Snow, Ice, and Aerosol Radiation) are being used to quantify how much carbon dioxide reduces albedo and how much additional melting it generates. An important advance is the integration of atmospheric-chemical models (e.g., GEOS-Chem, WRF-Chem) with snow models: this allows estimating carbon dioxide deposition from different sources and their radiative impact on glaciers.

- **Recent case studies in Andean countries:**
    - **Peru (Cordillera Blanca):**Schmitt et al. (2015) conducted one of the first detailed studies measuring BC in snow from several glaciers in the Cordillera Blanca. They found effective BC concentrations between ~4–25 ng/g on average annually (2012), with higher loads at low-lying sites near Huaraz. They concluded that areas near population centers have more contaminated snow and that the concentration decreases with altitude (less BC at higher glaciers). Subsequent studies in 2016–2017 (Sánchez Rodríguez & Schmitt) recorded much higher peaks of BC at specific glaciers: for example, Shallap and Vallunaraju (the closest to Huaraz) reached values of ~1000 ng/g in some samples during the dry season. In contrast, more distant glaciers such as Tocllaraju remained relatively low (<60 ng/g). These results confirmed the local urban influence. Furthermore, by comparing measurement techniques, they deduced that in the south of the Cordillera Blanca, anthropogenic BC predominates (soot-dominated absorption in snow near Huaraz), while in the north the contribution of natural dust is greater.
    - **Peru (Huaytapallana Mountain Range):**Torres et al. (2018) studied the Huaytapallana glacier (Junín, Peru) and found an average concentration of ~31 ng/g BC in snow (sampled in 2015-2016). Using SNICAR, they estimated that this caused an albedo reduction of 0.6–5%, which was more pronounced at the end of

the dry season. They noted that the highest depositions coincided with August, suggesting the arrival of smoke from Amazonian fires at that time. This study was pioneering in that mountain range and raised awareness about the incidence of pollution due to biomass burning in glaciers in central Peru.

- **Bolivia (Cordillera Real):**Osmont et al. (2019) analyzed ice cores from the Illimani glacier spanning hundreds of years. Using SP2, they measured BC trapped in different historical layers. They found that BC exhibits a marked seasonality: very low levels during the rainy seasons and high peaks during the dry season. A notable peak occurred during the 2007 drought, with ~58 ng/g (≈58 ppb) in ice from that date. They linked BC variations to the Amazon's fire history: periods of increased burning are reflected in higher BC levels at Illimani. In fact, comparing these with fire data, they suggest that BC deposition at Illimani has increased since the 1990s, consistent with increased fire activity in the Amazon basin. This is a key finding that highlights how recent glacial retreat may be additionally contributed to by increasing regional air pollution.
- **Bolivia (Cordillera Real, Zongo):**De Magalhães Neto et al. (2019) studied, through simulation, the effect of particles emitted by Amazonian fires on the Zongo glacier. Their results showed that deposited BC could reduce albedo by ~1.8–7.2%, while co-emitted dust could reduce it even further (up to 22% at high loads). They estimated that glacier mass loss due to co-deposition of BC and fire dust could be 3%–5% higher than without these impurities. This case highlights the importance of considering multiple pollutants and not just BC, since in tropical environments dust raised by fires or winds can enhance the effect of BC.
- **Colombia (Sierra Nevada de Santa Marta):**Bolaño-Ortiz et al. (2020) focused on the snow of the Sierra Nevada de Santa Marta, the only glacial massif in the tropical zone of northern South America. Using MODIS satellite data, they analyzed the relationship between snow reflectance (albedo), atmospheric aerosol presence, and meteorological variables from 2000 to 2020. They found that albedo variability was primarily correlated with atmospheric dust load (37% of the variation), while not clearly correlated with atmospheric BC or OC. However, they suggest that this is due to temporal resolution: punctual smoke events (BC) may not

be captured in satellite-based monthly averages. Their study implies that at that site, dust (possibly from La Guajira or other nearby arid areas) plays a more important role in the albedo of Colombia's last glaciers, rather than soot.

- **Regional integration (tropical Andes):** Bonilla et al. (2023) conducted an integrated study for the five most iconic tropical glaciers: Huascarán, Yanapaccha, Shallap (Peru, Cord. Blanca), Quelccaya (Peru, Cord. Oriental), and Illimani (Bolivia). They used observations (surface snow and ice cores) along with the GEOS-Chem and SNICAR snow models to quantify BC sources and radiative forcing. A key finding was the north-south difference: in glaciers from southern Peru and Bolivia, up to ~70–75% of the deposited BC comes from biomass burning (fires), while in the northwestern Andes (e.g., Huascarán, Peru) only ~25% comes from fires and the rest from fossil fuels (cities). That is, Illimani is dominated by smoke input, while Huascarán receives more urban soot (e.g., from Lima, Huaraz, or other sources). They also estimated the radiative forcing due to BC in snow: on average +0.5 to +2.1 W/m² in fresh snow and +1.5 to +6.3 W/m² in old snow on those glaciers (under clear skies). This forcing is substantial and compatible with accelerated melting. Their results are in agreement with historical measurements, e.g., they reproduced concentrations similar to those measured at Illimani by Osmont (12.4 ppb average 2014-19 vs. 1.1 ppb in 1998, suggesting an increase). Overall, this work confirms that BC from Amazonian fires is a critical factor for glaciers in southeastern Peru and Bolivia, while more northern glaciers also receive BC of local fossil origin. Furthermore, it highlights the importance of considering climatic conditions (clear vs. overcast skies) when assessing the impact (the forcing is slightly reduced in clouds, but remains significant).

The following table summarizes several relevant studies from the Andean region, indicating year, authors, location, methods used and main findings:

Year	**Authors (et al.)**	**Location (country)**	**Methods and data**	**Main findings**
2015	Schmitt, M. et al.	Cordillera Blanca (Peru)	Surface snow samples (LAHM);	Effective BC in snow: 4–25 ng/g (2012 annual average). Highest concentration in glaciers near

			altitudinal transect.	Huaraz; BC decreases with altitude. In the south of the mountain range, BC (of anthropogenic origin) dominates absorption; in the north, mineral dust contributes more.
2018	Torres, A. et al.	Huaytapallana Glacier (Peru)	Snow samples (2015-16, LAHM) + SNICAR modeling.	Average BC ~31 ng/g. Albedo reduction of 0.6% to 5% per BC deposited (greater in the dry season). Evidence of BC input from fires in the central Amazon.
2019	Osmont, D. et al.	Illimani Glacier (Bolivia)	Ice core (historical series) measured with SP2 (BC) and dust.	BC shows marked seasonality: peaks in the dry season associated with regional fires. Annual average ~1 ppb (1998); peak 58 ppb in 2007. Signal of increasing BC in recent decades consistent with an increase in Amazonian fires.
2019	de Magalhães, J. et al.	Zongo Glacier (Bolivia)	Atmospheric modeling (GFED emissions) + SNICAR.	Fire emissions (Amazon) deposit carbon dioxide and dust on the glacier. Carbon dioxide causes a 1.8–7.2% albedo reduction; dust at high concentrations, up to 22%. Co-deposition of carbon dioxide and dust could increase glacier mass loss by ~3–5%.
2020	Bolaño-Ortiz, T. et al.	Sierra Nevada de Santa Marta (Colombia)	Remote sensing (MODIS) of albedo + atmospheric	Atmospheric dust explained ~37% of the snow albedo variation (2000-2020). No significant correlation was found with

			aerosol reanalysis (MERRA).	atmospheric BC/OC on a monthly scale, likely due to underestimation of specific smoke events. This suggests that Saharan/regional dust plays an important role on this tropical glacier.
2021	Moya-Álvarez, A. et al.	Peruvian Andes (several glaciers)	Fire inventory (MODIS) + WRF-Chem and HYSPLIT (transport) modeling.	It identifies that the burning season in Peru begins in July and peaks in August-September. The mountain range most affected by wildfires is Huaytapallana (August), followed by Vilcabamba. The dominant flow comes from the north (Ucayali, Loreto), the main source of wildfires transported to glaciers in south-central Peru.
2023	Bonilla, E. et al.	Tropical Andes (Peru, Bolivia)	Observations on 5 glaciers (snow, ice) + GEOS-Chem (BC reservoir) and SNICAR (forcing) models.	~70–75% of BC in southern glaciers (Illimani, Quelccaya) comes from burned biomass, vs. ~25% in northwestern glaciers (Huascarán, Yanapaccha; remainder fossil). Radiative forcing by BC in snow: +0.5 to +2.1 W/m² (fresh snow) and +1.5 to +6.3 W/m² (old snow) under clear skies, contributing significantly to accelerated melting.

Comparative charts: Below are two figures that visually illustrate some recent quantitative results. Figure 1 shows the maximum concentrations of black carbon measured in surface snow on several Andean glaciers, highlighting the large spatial differences; Figure 2 shows the estimated albedo reduction attributable to BC at some of these sites.

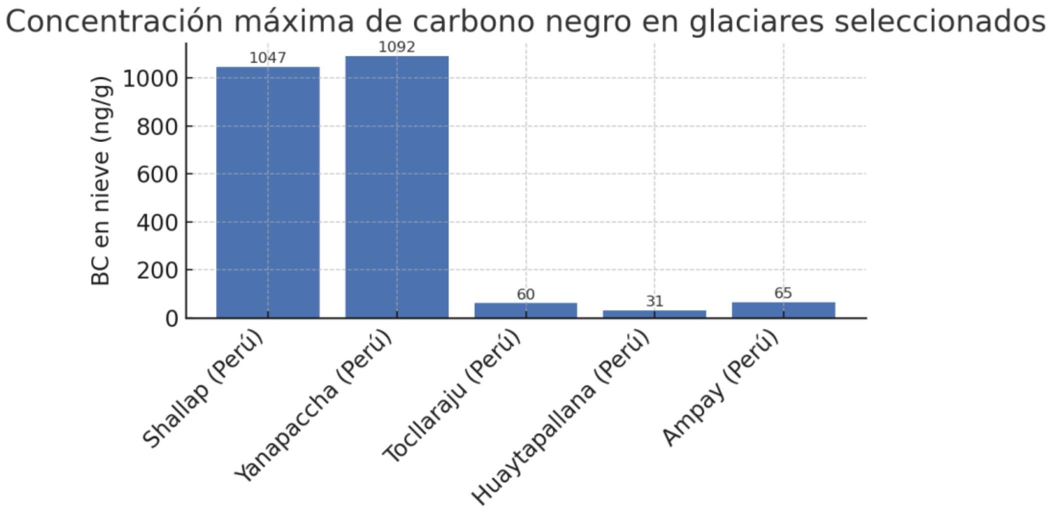

*Figure 1.*Maximum reported concentration of black carbon in surface snow from selected glaciers. Glaciers in the Cordillera Blanca (Peru: Shallap, Yanapaccha, Tocllaraju), the Huaytapallana Range (Peru), and the Vilcabamba Range (Peru: Ampay) are included. Data are from 2016–2017 measurements using LAHM: for example, Shallap and Yanapaccha reached around 1000 ng of BC per gram of snow (ng/g) during high pollution events in the dry season, while Tocllaraju (further from sources) remained below 60 ng/g. Huaytapallana and Ampay, in the central and southern Andes of Peru, showed intermediate values (tens of ng/g). These differences reflect the influence of proximity to urban and fire sources: Shallap (near Huaraz) received much more BC than Tocllaraju in the same mountain range, and Ampay (Cusco-Apurímac, surrounded by dry vegetation) exceeded Huaytapallana (Junín, a wetter area). In general, tropical Andean glaciers exhibit BC concentrations ranging from <10 ng/g under "clean" background conditions to peaks >1000 ng/g under situations strongly influenced by biomass burning or local human activity.

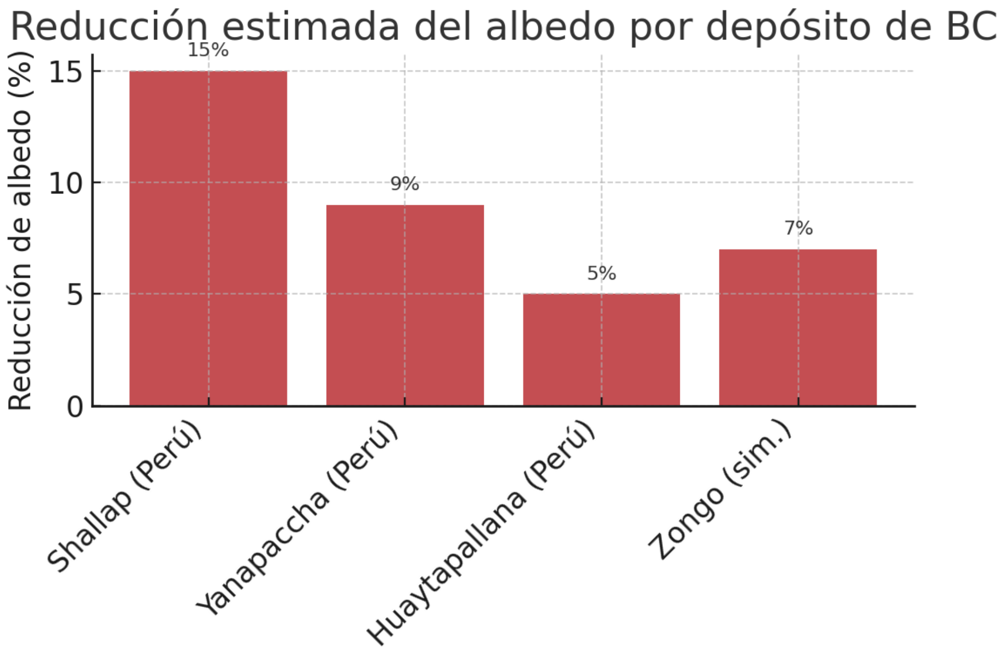

*Figure 2.*Estimated snow albedo reduction due to black carbon on various Andean glaciers. Values are based on studies using the SNICAR model or observations between 2015 and 2019. At Shallap (Peru), black carbon deposition caused a ~15% seasonal average albedo decrease; at Yanapaccha (Peru), it decreased by ~9%; and at Huaytapallana (Peru), up to ~5% during the dry season. By comparison, at Zongo Glacier (Bolivia), a ~7% reduction was simulated, attributable solely to black carbon from Amazonian fires. These figures indicate a considerable impact: albedo reductions of a few percent translate into several additional W/m² absorbed, accelerating melting. It is worth noting that where dust or algae coexist, the total darkening of the snow can be greater. For example, Saharan dust was also detected in the snow in Huaytapallana and Ampay, which, along with carbon dioxide, contributes to the observed albedo. In summary, carbon dioxide deposited on tropical glaciers leads to albedo losses of 5–15%, which exacerbates their retreat under climate change.

Critical synthesis and perspectives

Recent studies have significantly improved our understanding of black carbon in tropical Andean glaciers; however, significant gaps in knowledge remain:

- **Limited data and insufficient geographical coverage:**Observations of BC in snow in the tropical Andes are still scarce and scattered. As of 2022, most data come from a few mountain ranges in Peru (Blanca, Vilcabamba) and Bolivia (Real), with very little information from countries such as Ecuador or Colombia. This lack of data hampers a systematic understanding of transport and deposition processes across the region. Measurements need to be extended to other tropical glaciers (e.g., the Eastern Cordillera of Ecuador, the Sierra de Merida in Venezuela, if present, etc.) to gain a more complete picture.

- **Distinction of sources and components:**The relative proportion of BC from biomass burning versus fossil fuels deposited on each glacier is still not precisely known. Studies such as Bonilla 2023 are beginning to address this with models, but more in situ measurements of chemical markers (e.g., levoglucosan for biomass, sulfates for fossils) are needed to attribute origins. Similarly, the contribution of mineral dust versus BC to radiation absorption in snow needs to be better differentiated. Most studies measured optical "equivalent BC," which includes dust absorption; further combined analyses (pure BC by SP2 + dust composition) are needed to quantify each component.
- **Post-deposition processes and bio-albedo:**Once carbon dioxide falls onto a glacier, the processes that determine its fate (burial by snowfall, wind redistribution, cryoconite formation, biological activity) have not been characterized in detail in the Andes. For example, how much carbon dioxide is trapped in snowfall versus how much is released into rivers through seasonal melting is unknown. Another gap is the role of organisms (snow/ice algae) in surface darkness: Arctic research suggests that algal blooms can drastically reduce albedo and may be occurring on Andean glaciers due to warming, but there are virtually no local studies on this topic. The interaction between carbon dioxide particles and surface biology (e.g., carbon dioxide can provide nutrients to algae, promoting their growth) is an emerging topic to be explored.
- **Uncertainty in regional climate models:**Although progress has been made in incorporating the effect of BC into glacial mass balance models, uncertainties persist in the projections. For example, future BC emission scenarios in South America are not well-defined: will burning decrease due to controlled deforestation or increase with drought? Furthermore, the representation of aerosol deposition in global models is often coarse for mountainous terrain. This introduces uncertainty into predictions of glacial evolution in the Andes. Improving models requires "a deep understanding of the origin of LAPs and their occurrence in the Andean atmosphere and cryosphere," including realistic optical

properties of the particles (e.g., considering internal/external mixing of BC and dust, which alter absorption).

Looking to the future, several lines of research are considered priorities:

- Establish continuous monitoring programs for BC deposition on Sentinel glaciers (e.g., Huascarán, Illimani), with systematic seasonal sampling. This would allow for identifying interannual background trends and correlating them with emissions and fire data.
- Implement high-altitude atmospheric observatories in the Andes (similar to stations in the Himalayas) to measure high-altitude aerosol concentrations and deposited flux. For example, a sun photometer and particle sampler in a glacial refuge could capture smoke transport events.
- Investigate the bioalbedo phenomenon in tropical glaciers: look for evidence of red or green algae in Andean snow, quantify their effect, and determine whether BC is contributing indirectly (by providing iron or other nutrients).
- Refine optical property measurements of Andean dirty snow. Use hyperspectral sensors in the field or using drones to detect signatures of carbon dioxide, dust, and algae, thus feeding into region-specific satellite algorithms.
- Develop local mitigation strategies: For example, in the Cordillera Blanca, better control of vehicle emissions and garbage burning in Huaraz could reduce the BC load on neighboring glaciers. Evaluating the potential impact of such measures on glacial balance would be valuable for public policy.
- Explore local geoengineering: Although controversial, there is debate about whether it is feasible to "clean" or cover highly strategic sections of glaciers (e.g., those that supply drinking water) with reflective tarpaulins to temporarily counteract the effects of BC. Any such intervention would first require a solid understanding of deposition dynamics.

In terms of environmental management and adaptation, the findings on BC in glaciers are highly relevant. Tropical Andean glaciers are critical sources of freshwater for ~77 million people, feeding rivers used in agriculture, human consumption, and hydroelectric generation. The observed accelerated glacial retreat (loss of >30–50% of area in many areas since the 1980s) is primarily due to climate change (increasing temperatures), but black carbon deposition acts as an amplifier of warming in high mountains. This implies that reducing BC emissions may be a short-term climate action measure to help conserve glaciers. Unlike CO_2, BC has a short atmospheric lifetime; if burning and local pollution are drastically reduced, the atmosphere would clear within days or weeks, and deposition on snow would decrease. Therefore, forest fire control policies, agricultural burning management, and diesel emissions reduction in Andean countries could yield direct benefits in slowing glacier mass loss (in addition to public health benefits from reduced pollution). International organizations have identified BC as a short-lived climate pollutant whose mitigation generates a double dividend: it improves air quality and helps limit global warming in sensitive regions.

In conclusion, the state of the art indicates that black carbon is a significant factor in the Andean tropical cryosphere. Progress has been made in identifying its sources (predominantly biomass burning), its transport patterns (long distances from the Amazon), and its effects (albedo reduction and increased glacial melting). However, much research remains to be done to accurately quantify its contribution to the energy balance of each glacier and project its influence under different future scenarios. Filling these knowledge gaps is vital to understanding the complex response of tropical glaciers to global change and to designing adaptation and mitigation measures that ensure water availability and stability of mountain ecosystems in the Andes. As one study notes, “although black carbon is not the primary cause of the disappearance of Andean glaciers, it could well be the 'straw that melts the ice,' accelerating a process already underway.”

BIBLYOGRAPHY