



Brief communication: Dose-dependent enhancement of snow mass loss by biomass-burning carbonaceous particles on a tropical Andean glacier

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Abstract. We conducted a replicated 9 h field experiment on Artesonraju Glacier, Peru, to quantify snow mass loss under surface loadings (0–1052.3 mg m⁻²) of biomass-burning-derived carbonaceous particles. Common background snow minimized mineral-dust confounding and isolated the incremental effect of added combustion-derived particles. Total snow mass loss increased almost linearly with loading ($R^2 = 0.997$), with a sensitivity of 0.0089 mm w.e. per mg m⁻². Drainage-related mass loss increased by $1.2 \pm 0.9\%$ at 10.5 mg m⁻² and $14.7 \pm 6.0\%$ at 1052.3 mg m⁻². These results show that fire-derived particles can measurably enhance tropical Andean glacier snow loss.

1. Introduction

Light-absorbing carbonaceous particles deposited on snow reduce surface albedo and increase the absorption of solar radiation, providing a well-established physical mechanism for enhanced snowmelt (Warren and Wiscombe, 1980; Conway et al., 1996). However, while observations of naturally contaminated snow and corresponding radiative-transfer modeling of snow albedo changes have been extensively investigated (Gilardoni et al., 2022), controlled experiments directly quantifying the snowmelt response to added carbonaceous particles remain comparatively scarce (e.g. Conway et al., 1996; Brandt et al., 2011; Svensson et al., 2016; Svensson et al., 2024).

The limited experimental literature has addressed different components of the relationship between carbonaceous particles and snowpack response (Table S1). Conway et al. (1996) conducted one of the earliest field manipulations on glacier snow by applying soot and volcanic ash to Blue Glacier, USA, showing that residual soot reduced albedo by approximately 30 % and increased melting by approximately 50 %. Brandt et al. (2011) subsequently produced artificial snowpacks with and without soot to experimentally test



the relationship between black carbon (BC) concentration and albedo reduction. Both studies deliberately used concentrations substantially above natural background levels to generate a detectable optical and melt response. Furthermore, field experiments on natural seasonal snow in Finland (the SoS experiments) demonstrated changes in albedo, snow density, particle retention, and snow metamorphism following artificial soot deposition (Meinander et al., 2014; Peltoniemi et al., 2015; Svensson et al., 2016). Additionally, the SoS-2011 experiment showed that soot-contaminated snow melted faster than nearby reference snow (Svensson et al., 2016), whereas subsequent SoS experiments examined different particle loadings and their influence on snow properties and snow-cover duration (Svensson et al., 2024). Beres et al. (2020) further deposited carbonaceous aerosols generated from smoldering peat onto natural snow in the Sierra Nevada, USA, quantifying changes in spectral albedo and radiative forcing. This provided an experimental analogue for biomass-burning aerosol deposition, albeit without directly measuring subsequent snow mass loss.

Despite substantial advances in observations and modeling, direct quantification of the melting effect produced by light-absorbing particles after deposition onto snow remains limited and warrants further experimental investigation (Gilardoni et al., 2022; Svensson et al., 2024). Thus, although experimental evidence demonstrates both optical responses and enhanced ablation, replicated field experiments directly resolving a dose-response relationship between increased carbonaceous particle loading and snow mass loss remain notably limited.

This experimental gap is particularly relevant in the tropical Andes, where biomass burning represents an important source of carbonaceous particles deposited on glaciers (Magalhães et al., 2019; Gilardoni et al., 2022; Bonilla et al., 2023). Magalhães et al. (2019) demonstrated atmospheric transport of Amazonian biomass-burning aerosols to the central Andes and estimated that biomass-burning BC could increase the absorbed energy and annual melt of tropical Andean glaciers through the BC-albedo effect. Their simulations for Zongo Glacier indicated an approximately 3.3 ± 0.8 % increase in annual melting attributable to biomass-burning BC under low-dust conditions. More recently, Bonilla et al. (2023), combining GEOS-Chem simulations with observations from Peruvian and Bolivian glaciers, estimated that smoke from fires accounts for approximately 20–70 % of total wet and dry BC deposition, depending on the glacier site, with a corresponding positive radiative forcing over Andean snow. Despite this strong atmospheric connection between South American biomass burning and the Andean



cryosphere, the resulting glacier response has been investigated predominantly through albedo change and radiative modeling (Magalhães et al., 2019; Bonilla et al., 2023), alongside water drainage observations and melt modeling (Magalhães et al., 2019), rather than through replicated, controlled physical manipulations directly measuring snow mass loss.

Here, we revisit a field experiment conducted on Artesonraju Glacier in the Cordillera Blanca, Peru, designed to quantify the short-term sensitivity of glacier snow to increasing surface loadings of biomass-burning-derived carbonaceous particles. The experimental material was produced through the combustion of wood and grass and was subsequently characterized as predominantly carbonaceous, with irregular particle morphology. Snow was exposed for 9 h under natural glacier conditions to five increasing particle loadings (0.1, 0.5, 1, 5, and 10 mg) and an unamended control, using perforated and unperforated containers with three independent replicates of each treatment in each container type. Snow mass was measured repeatedly throughout the experiment. We test whether increasing carbonaceous-particle loading produces a measurable dose-dependent enhancement of snow mass loss under field conditions. To our knowledge, this represents the first replicated controlled dose-response field experiment directly quantifying short-term gravimetric snow mass loss across increasing loadings of biomass-burning-derived carbonaceous particles on a tropical Andean glacier.

2. Materials and methods

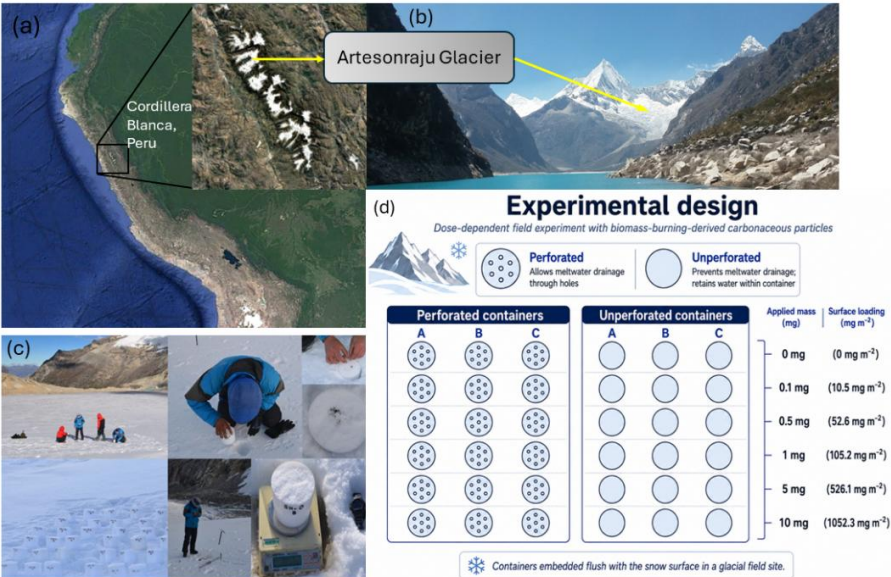
2.1 Field experiment

The field experiment was conducted on Artesonraju Glacier, Cordillera Blanca, Peru, at ~4950.0 m a.s.l. on 1 June 2017 between 09:00 and 18:00 local time (Fig. 1a and b). Experimental units consisted of snow exposed under natural glacier conditions in transparent plastic containers with an internal diameter of 11 cm, corresponding to an exposed surface area of 0.009503 m². Six particle treatments were applied: 0 (control), 0.1, 0.5, 1, 5, and 10 mg per experimental unit, equivalent to surface loadings of 0, 10.5, 52.6, 105.2, 526.1, and 1052.3 mg m⁻², respectively (Table S2). Each treatment was replicated three times in both perforated and unperforated containers, resulting in 36 experimental units (Fig. 1c and d).

Perforated containers allowed meltwater to drain from the experimental units; therefore, their mass change was interpreted as total mass loss, integrating meltwater drainage and atmospheric mass losses. In unperforated containers, meltwater was



106 retained, so the measured mass change represented atmospheric mass loss, including
107 sublimation and potentially evaporation. The difference between perforated and
108 unperforated containers was consequently interpreted as drainage-related mass loss and
109 used as a proxy for meltwater drainage. Experimental units were weighed at 09:00, 12:00,
110 15:00, and 18:00 local time, providing a 9 h daytime record of snow mass loss.



111
112 **Figure 1. Study site and experimental design on Artesonraju Glacier, Cordillera Blanca,**
113 **Peru.** (a) Location of the Cordillera Blanca and Artesonraju Glacier in Peru (Map data © 2025
114 Google Earth). (b) View of Artesonraju Glacier and the surrounding valley. (c) Field photographs
115 showing installation of the experimental units and weighing procedures on the glacier surface. (d)
116 Schematic representation of the experimental design, including perforated and unperforated
117 containers, three replicates per treatment, and the applied particle masses and corresponding
118 surface loadings.

119 To place the experimental loadings in an environmental context, they were
120 compared with modeled fire-derived BC deposition over tropical Andean glacier regions
121 using the GEOS-Chem simulations of Bonilla et al. (2023) (Fig. S1a-d). For August–
122 October 2017, modeled fire-derived BC deposition was approximately 6.2 mg m⁻² over
123 the Cordillera Blanca and 21.6 mg m⁻² over the Cordillera Real, Bolivia. Thus, the lowest
124 experimental loading (10.5 mg m⁻²) was of the same order of magnitude as modeled fire-
125 derived BC deposition in Andean glacier environments, whereas the higher treatments
126 were used to characterize the dose-response relationship under progressively stronger
127 surface-particle loadings. Field observations further illustrate that pronounced glacier-
128 surface darkening can occur in the Cordillera Blanca during and near the end of the



129 regional fire season. Photographs from Artesonraju Glacier on 3 September 2025 and
 130 nearby Yanapaccha Glacier on 5 November 2017 show strongly darkened glacier surfaces
 131 under natural conditions (Fig. S2). Because the exact BC fraction of the experimentally
 132 generated material was not determined, this comparison is intended to provide an
 133 environmental order-of-magnitude context rather than imply direct compositional
 134 equivalence.

135 The applied material consisted of finely ground biomass-burning char produced
 136 by combustion of a mixture of wood and grass in a container covered with aluminum foil.
 137 The resulting material was collected, macerated, and sieved through a cascade sieve
 138 system to retain the finer particle fraction prior to application to the snow surface. Particle
 139 morphology and elemental composition were characterized by scanning electron
 140 microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS), whereas
 141 particle-size distribution was determined by laser diffraction using a CILAS 1064
 142 particle-size analyzer. The material was predominantly carbonaceous, had a visibly black,
 143 char-like appearance, exhibited irregular particle morphology, and showed a broad size
 144 distribution with modal sizes of approximately 17.5 and 31 μm (Fig. S3). In addition to
 145 the dominant C signal, EDS detected minor amounts of O, K, Fe, Mg, Ca, Na, Cl, and
 146 Mo, consistent with the presence of inorganic constituents commonly associated with
 147 biomass. Samples were gold-coated prior to SEM analysis; consequently, the Au signal
 148 detected by EDS originated from sample preparation. Because aluminum foil was used
 149 during particle production, part of the Al signal detected by EDS may also reflect
 150 contamination introduced during this procedure.

151

152 **2.2 Meteorological data and regression analysis**

153 Meteorological conditions during the experiment were characterized using
 154 measurements from an automatic weather station located in the Artesonraju Glacier. Air
 155 temperature, relative humidity, wind speed, and precipitation were recorded at 30 min
 156 intervals. During the experimental period (09:00–18:00 local time), air temperature
 157 ranged from 1.97 to 7.62 $^{\circ}\text{C}$, relative humidity from 56.1 to 80.2 %, and wind speed from
 158 0.51 to 6.96 m s^{-1} . The experiment was conducted on visually clean glacier snow shortly
 159 after a recent precipitation period (~ 6.2 mm between 25 and 30 May 2017), consistent
 160 with relatively recent snow deposition. No precipitation was recorded during the
 161 experiment or at any time on 1 June 2017.



162 Snow mass was measured at 09:00, 12:00, 15:00, and 18:00 local time. Mass
 163 changes were converted to water-equivalent units by normalizing to the exposed surface
 164 area of each experimental unit (0.009503 m^2), using the equivalence $1 \text{ kg m}^{-2} = 1 \text{ mm}$
 165 w.e. Final total snow mass loss after 9 h was evaluated as a function of particle surface
 166 loading. A linear regression was used to quantify the dose-response relationship between
 167 particle loading and final total snow mass loss. The regression slope was interpreted as
 168 the daytime-integrated sensitivity of snow mass loss to particle surface loading over the
 169 9 h experimental period, rather than as a climatological ablation rate.

170

171 **3. Results**

172 Figure 2a illustrates the condition of the snow at the beginning and end of the
 173 experiment for the three unperforated replicates receiving the highest particle surface
 174 loading (1052 mg m^{-2}). Photographs documenting the initial and final conditions of all
 175 experimental units across the full particle-loading range are provided in Figs. S4 and S5,
 176 respectively. During the 9 h experiment, sky conditions varied between partly cloudy (~ 4
 177 h) and predominantly sunny (~ 5 h). Meteorological conditions changed markedly through
 178 the day (Fig. 2b): air temperature increased from approximately 2°C in the early morning
 179 to a maximum of 7.6°C in the early afternoon, while wind speed was highest during the
 180 first hours and generally decreased thereafter.

181 These changes were accompanied by distinct temporal patterns in the measured
 182 mass-loss components (Fig. 2c). During the first hours, when air temperature was
 183 relatively low and wind speed was comparatively high, drainage-related mass loss
 184 remained limited, whereas atmospheric mass loss increased. As air temperature rose later
 185 in the day, and wind speed decreased, atmospheric mass loss reduced, while drainage-
 186 related mass loss increased progressively and became the dominant component of total
 187 snow mass loss. Snow mass loss increased throughout the 9 h experiment in all
 188 treatments, with the largest cumulative losses occurring under the highest particle
 189 loadings (Fig. 2c).

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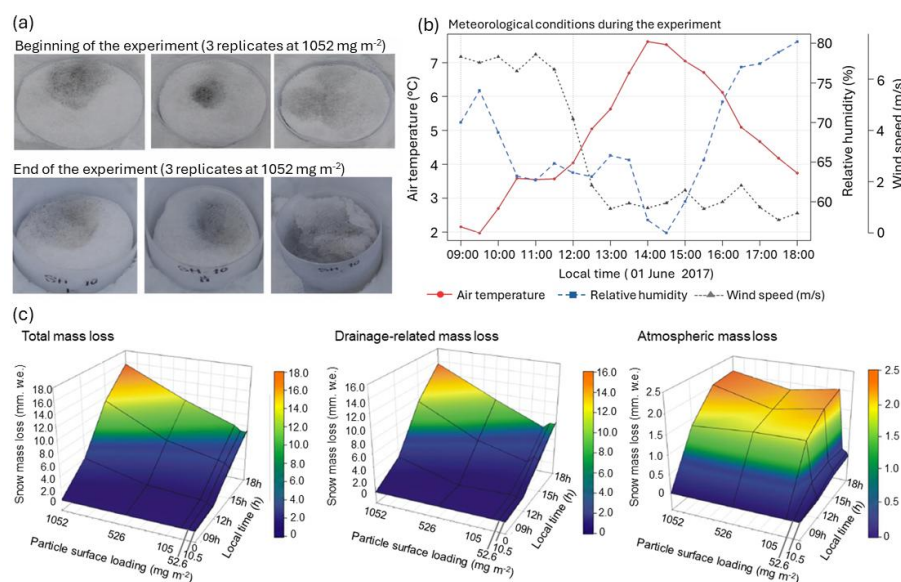


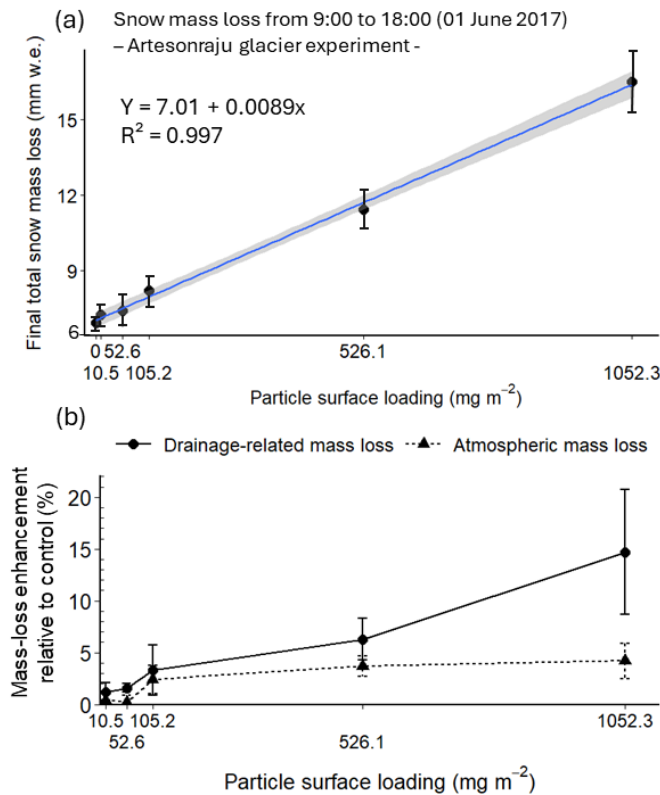
Figure 2. Temporal evolution of snow mass loss during the 9 h field experiment on Artesonraju Glacier. (a) Experimental units at the beginning (09:00) and end (18:00) of the experiment for the highest particle surface loading (1052 mg m⁻²), showing the three independent replicates. (b) Meteorological conditions during the experiment, including air temperature, relative humidity, and wind speed measured between 09:00 and 18:00 local time on 1 June 2017. (c) Evolution of snow mass loss as a function of particle surface loading and time for total mass loss, drainage-related mass loss, and atmospheric mass loss. Total mass loss was measured in perforated containers, atmospheric mass loss in unperforated containers, and drainage-related mass loss was calculated as the difference between the two experimental configurations. Snow mass loss is expressed in millimeters of water equivalent (mm w.e.).

Final total snow mass loss showed a clear dose-dependent increase with particle surface loading (Fig. 3a). After 9 h, mean total mass loss increased from approximately 6.90 mm w.e. in the untreated control to 16.5 mm w.e. at the highest loading (1052.3 mg m⁻²). The relationship was strongly linear across the experimental range ($y=7.01+0.0089x$, $R^2=0.997$). The regression slope indicates an increase of approximately 0.0089 mm w.e. in final snow mass loss for each additional 1 mg m⁻² of particle loading over the 9 h experimental period, equivalent to approximately 0.89 mm w.e. per 100 mg m⁻².

The relative enhancement of mass loss also differed between the two experimental components (Fig. 3b). Drainage-related mass loss increased progressively with particle loading, reaching 14.7 ± 6.0 % above the control at 1052.3 mg m⁻². The corresponding enhancements were 1.2 ± 0.9 , 1.6 ± 0.4 , 3.3 ± 2.4 , and 6.3 ± 2.0 % at 10.5, 52.6, 105.2, and



216 526.1 mg m⁻², respectively. Atmospheric mass loss showed a smaller response, with
217 enhancements of 0.2±0.7, 0.4±0.1, 2.4±1.4, 3.7±1.0, and 4.2±1.7 % across the same
218 increasing loadings. Thus, the largest particle-induced increase in snow mass loss was
219 associated with the drainage-related component. A summary of the final experimental
220 results across all particle-loading levels is provided in Table S3.
221



222 **Figure 3. Dose-response of snow mass loss to increasing surface loadings of biomass-**
223 **burning-derived carbonaceous particles.** (a) Final total snow mass loss after the 9 h experiment
224 as a function of particle surface loading. Points represent mean values for the three experimental
225 replicates and error bars indicate standard deviation. A linear regression was fitted to the mean
226 final total snow mass loss across the six particle-loading levels, and a 95 % confidence interval
227 was calculated for the fitted relationship. The blue line represents the linear regression
228 ($y=7.01+0.0089x$, $R^2=0.997$), and the shaded area denotes the 95 % confidence interval. (b)
229 Enhancement of drainage-related and atmospheric mass loss relative to the untreated control as
230 a function of particle surface loading. Symbols represent mean percentage enhancement and error
231 bars indicate standard deviation.
232

233



4. Discussion

Increasing surface loadings of biomass-burning-derived carbonaceous particles produced a clear, near-linear dose-dependent increase in short-term snow mass loss on Artesonraju Glacier. The regression slope of 0.0089 mm w.e. per mg m⁻² represents the daytime-integrated sensitivity of snow mass loss to particle loading over the 9 h experiment and should not be interpreted as a climatological ablation rate or a transferable glacier-wide melt factor. The predominance of the drainage-related response indicates that the strongest particle-induced enhancement was associated with increased liquid-water drainage, whereas atmospheric mass loss showed a substantially smaller response.

Previous field and laboratory experiments have established that soot and other light-absorbing particles reduce snow albedo and can accelerate melt (Conway et al., 1996; Brandt et al., 2011; Svensson et al., 2016, 2024; Beres et al., 2020). Recently, observations from High Mountain Asia demonstrate that BC deposited in glacier snow can translate into substantial meltwater production (González-Santacruz et al., 2025) and contribute measurably to reduce solid water storage at regional scales (Yang et al., 2025).

Among light-absorbing impurities, mineral dust can also substantially reduce snow albedo, complicating the attribution of observed albedo and melt responses to carbonaceous particles in natural Andean glacier environments. Field observations in the Chilean Andes have shown that dust can account for a substantial fraction of light absorption in snow (Rowe et al., 2019), while controlled experiments with Andean mineral dust demonstrated concentration-dependent reductions in snow albedo (Pacheco-Ferrada et al., 2024). Dust-driven albedo changes have also been quantified at Nevado Huascarán in the Cordillera Blanca (Weber et al., 2026), while recent glacier-scale simulations in the European Alps showed that mineral dust can substantially affect summer surface mass balance, with interactions between dust and BC further influencing the modeled response (Roussel et al., 2025). In the present experiment, treated and control units shared the same background snow and environmental conditions, while only the amount of added biomass-burning-derived carbonaceous material was systematically varied. This design therefore minimizes confounding by differences in background mineral-dust loading among treatments, allowing the incremental response to the added combustion-derived particles to be evaluated experimentally.

Accordingly, the present experiment provides direct evidence that the addition of biomass-burning-derived carbonaceous particles can enhance snow mass loss while minimizing confounding from between-treatment differences in background mineral-dust



loading. Importantly, the lower end of the experimental loading range is comparable in order of magnitude to modeled fire-derived BC deposition over Andean glaciers (Bonilla et al., 2023). At 10.5 mg m^{-2} , drainage-related and atmospheric mass loss increased by $1.2 \pm 0.9 \%$ and $0.2 \pm 0.7 \%$, respectively. Although the timescales and response metrics are not directly comparable, these short-term responses are broadly consistent in magnitude with the $3.3 \pm 0.8 \%$ increase in annual melt attributed to biomass-burning BC under low-dust conditions at Zongo Glacier, Bolivia (Magalhães et al., 2019), supporting the environmental plausibility of the lower end of the experimental range.

The higher experimental loadings primarily served to characterize the response under progressively stronger surface contamination. Such conditions may also approximate episodes of post-depositional surface enrichment, as particles can become concentrated at the snow surface during snow metamorphism, melt-freeze cycling, and sublimation. Bonilla et al. (2023) similarly discussed post-depositional processes that can enhance particle concentrations at Andean glacier surfaces. Field observations from Artesonraju and nearby Yanapaccha glaciers further illustrate that strongly darkened glacier surfaces can occur under natural conditions during and near the end of the regional fire season (Fig. S2).

The experiment represents a 9 h daytime exposure and therefore captures the particle response under the meteorological conditions encountered during that period rather than the full range of conditions experienced by the glacier. The use of biomass-burning-derived carbonaceous particles provides an environmentally relevant representation of combustion-derived material from vegetation fires that may be deposited on glacier surfaces. The container configuration was held constant within treatment-control comparisons, allowing relative particle-induced effects to be evaluated under the same experimental setup. The experiment was designed to quantify snow mass loss directly rather than radiative forcing, and the observed sensitivity should therefore not be extrapolated directly to other meteorological conditions or to daily, seasonal, or glacier-wide mass loss. Further field experiments conducted under a broader range of meteorological and surface conditions are needed to constrain the magnitude and variability of the effect of biomass-burning-derived carbonaceous particles on tropical Andean glacier snow loss.



5. Conclusion

This field experiment on Artesonraju Glacier demonstrates a clear dose-dependent increase in short-term snow mass loss with increasing surface loadings of biomass-burning-derived carbonaceous particles. At the lower end of the experimental range, drainage-related mass loss increased by 1.2 ± 0.9 % relative to the control at 10.5 mg m^{-2} and by 1.6 ± 0.4 % at 52.6 mg m^{-2} , with the response increasing progressively across the experimental range to 14.7 ± 6.0 % at the highest loading (1052.3 mg m^{-2}). These results provide direct experimental evidence that biomass-burning-derived particles can enhance snow mass loss under natural tropical Andean glacier conditions and establish a basis for more targeted experiments across different Andean glaciers, seasons, and meteorological and radiative conditions, thereby helping to reduce uncertainties in their contribution to glacier mass loss.

Data availability. The experimental data underlying the results presented in this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.22165974>. Meteorological data and GEOS-Chem modeled fire-derived black carbon deposition data were obtained from Mickley and Bonilla (2023) and are available at <https://doi.org/10.7910/DVN/KXVX0J>.

L. Mickley and E. Bonilla, “Contribution of biomass burning to black carbon deposition on Andean glaciers: Consequences for radiative forcing.” Harvard Dataverse, 2023. doi: 10.7910/DVN/KXVX0J.

Supplement. The supplement related to this article is available online.

Author contributions. NM and HE conceived and designed the study. NM conducted the data analysis and visualization and prepared the original manuscript draft. HE contributed to data interpretation and reviewed and edited the manuscript. WSR conducted the field investigation, contributed to data curation, and reviewed the manuscript. All authors reviewed and approved the final version of the manuscript.

Competing interests. The contact author has declared that neither of the authors has any competing interests.



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341

342 **Acknowledgements.** We gratefully acknowledge the Autoridad Nacional del Agua
 343 (ANA), Peru, for making this study possible and for providing logistical support during
 344 fieldwork on Artesonraju Glacier.

345

346 **Financial support.** This research was supported by the Brazilian National Council for
 347 Scientific and Technological Development (CNPq).

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349 References

350 Beres, N. D., Sengupta, D., Samburova, V., Khlystov, A. Y., and Moosmüller, H.:
 351 Deposition of brown carbon onto snow: changes in snow optical and radiative
 352 properties, *Atmos. Chem. Phys.*, 20, 6095–6114, [https://doi.org/10.5194/acp-20-](https://doi.org/10.5194/acp-20-6095-2020)
 353 [6095-2020](https://doi.org/10.5194/acp-20-6095-2020), 2020.

354 Bonilla, E. X., Mickley, L. J., Beaudon, E. G., Thompson, L. G., Rodriguez, W. E., Cruz
 355 Encarnación, R., Whicker, C. A., Flanner, M. G., Schmitt, C. G., and Ginot, P.:
 356 Contribution of biomass burning to black carbon deposition on Andean glaciers:
 357 consequences for radiative forcing, *Environ. Res. Lett.*, 18, 024031,
 358 <https://doi.org/10.1088/1748-9326/acb371>, 2023.

359 Brandt, R. E., Warren, S. G., and Clarke, A. D.: A controlled snowmaking experiment
 360 testing the relation between black carbon content and reduction of snow albedo, *J.*
 361 *Geophys. Res.-Atmos.*, 116, D08109, <https://doi.org/10.1029/2010JD015330>,
 362 2011.

363 Conway, H., Gades, A., and Raymond, C. F.: Albedo of dirty snow during conditions of
 364 melt, *Water Resour. Res.*, 32, 1713–1718, <https://doi.org/10.1029/96WR00712>,
 365 1996.

366 Gilardoni, S., Di Mauro, B., and Bonasoni, P.: Black carbon, organic carbon, and mineral
 367 dust in South American tropical glaciers: A review, *Global Planet. Change*, 213,
 368 103837, <https://doi.org/10.1016/j.gloplacha.2022.103837>, 2022.

369 González-Correa, S., Gómez-Doménech, D., Ballesteros, R., Lapuerta, M., Pacheco-
 370 Ferrada, D., Flores, R. P., Castro, L., Fadic-Ruiz, X., and Cereceda-Balic, F.: Impact
 371 of vehicle soot agglomerates on snow albedo, *Atmosphere*, 13, 801,
 372 <https://doi.org/10.3390/atmos13050801>, 2022a.



- 373 González-Correa, S., Lapuerta, M., Ballesteros, R., Pacheco-Ferrada, D., Castro, L., and
 374 Cereceda-Balic, F.: Impacts of soot, ash, sand, and haze on snow albedo in Sierra
 375 Nevada, Spain, *Atmosphere*, 13, 1903, <https://doi.org/10.3390/atmos13111903>,
 376 2022b.
- 377 González-Santacruz, N., Fernandoy, F., Goto-Azuma, K., Hirabayashi, M., Cordero, R.
 378 R., Feron, S., and Faria, S. H.: Black carbon effects and seasonal isotope records in
 379 the Godwin-Austen snowpack and K2 high-altitude camps, *J. Glaciol.*, 71, e22,
 380 <https://doi.org/10.1017/jog.2024.111>, 2025.
- 381 Lapuerta, M., González-Correa, S., Ballesteros, R., Cereceda-Balic, F., and Moosmüller,
 382 H.: Albedo reduction for snow surfaces contaminated with soot aerosols:
 383 Comparison of experimental results and models, *Aerosol Sci. Technol.*, 56, 847–
 384 858, <https://doi.org/10.1080/02786826.2022.2091975>, 2022.
- 385 Magalhães, N., Evangelista, H., Condom, T., Rabatel, A., and Ginot, P.: Amazonian
 386 biomass burning enhances tropical Andean glaciers melting, *Sci. Rep.*, 9, 16914,
 387 <https://doi.org/10.1038/s41598-019-53284-1>, 2019.
- 388 Meinander, O., Kontu, A., Virkkula, A., Arola, A., Backman, L., Dagsson-
 389 Waldhauserová, P., Järvinen, O., Manninen, T., Svensson, J., de Leeuw, G., and
 390 Leppäranta, M.: Brief communication: Light-absorbing impurities can reduce the
 391 density of melting snow, *The Cryosphere*, 8, 991–995, [https://doi.org/10.5194/tc-8-](https://doi.org/10.5194/tc-8-991-2014)
 392 [991-2014](https://doi.org/10.5194/tc-8-991-2014), 2014.
- 393 Pacheco-Ferrada, D., Castro, L., González-Correa, S., Lapuerta, M., Ruggeri, M. F., and
 394 Cereceda-Balic, F.: Optical effect of Andean mineral dust onto snow surface
 395 spectral albedo, *Atmos. Environ.*, 333, 120608,
 396 <https://doi.org/10.1016/j.atmosenv.2024.120608>, 2024.
- 397 Peltoniemi, J. I., Gritsevich, M., Hakala, T., Dagsson-Waldhauserová, P., Arnalds, Ó.,
 398 Anttila, K., Hannula, H.-R., Kivekäs, N., Lihavainen, H., Meinander, O., Svensson,
 399 J., Virkkula, A., and de Leeuw, G.: Soot on Snow experiment: bidirectional
 400 reflectance factor measurements of contaminated snow, *The Cryosphere*, 9, 2323–
 401 2337, <https://doi.org/10.5194/tc-9-2323-2015>, 2015.
- 402 Rowe, P. M., Cordero, R. R., Warren, S. G., Stewart, E., Doherty, S. J., Pankow, A.,
 403 Schrempf, M., Casassa, G., Carrasco, J., Pizarro, J., MacDonell, S., Damiani, A.,
 404 Lambert, F., Rondanelli, R., Huneeus, N., Fernandoy, F., and Neshyba, S.: Black
 405 carbon and other light-absorbing impurities in snow in the Chilean Andes, *Sci. Rep.*,
 406 9, 4008, <https://doi.org/10.1038/s41598-019-39312-0>, 2019.
- 407 Roussel, L., Dumont, M., Réveillet, M., Six, D., Kneib, M., Nabat, P., Fourteau, K.,
 408 Monteiro, D., Gascoin, S., Thibert, E., Rabatel, A., Sicart, J.-E., Bonnefoy, M.,
 409 Piard, L., Laarman, O., Jourdain, B., Fructus, M., Vernay, M., and Lafaysse, M.:
 410 Saharan dust impacts on the surface mass balance of Argentière Glacier (French



- 411 Alps), *The Cryosphere*, 19, 5201–5230, <https://doi.org/10.5194/tc-19-5201-2025>,
412 2025.
- 413 Svensson, J., Virkkula, A., Meinander, O., Kivekäs, N., Hannula, H.-R., Järvinen, O.,
414 Peltoniemi, J. I., Gritsevich, M., Heikkilä, A., Kontu, A., Neitola, K., Brus, D.,
415 Dagsson-Waldhauserová, P., Anttila, K., Vehkamäki, M., Hienola, A., de Leeuw, G.,
416 and Lihavainen, H.: Soot-doped natural snow and its albedo - results from field
417 experiments, *Boreal Environ. Res.*, 21, 481–503, 2016.
- 418 Svensson, J., Leppänen, L., Hannula, H.-R., Kontu, A., Shen, Y.-C., Meinander, O.,
419 Dagsson-Waldhauserová, P., Mesceriakovas, A., Heikkinen, E., Ruppel, M.,
420 Sippula, O., Ström, J., Asmi, E., and Virkkula, A.: Soot-on-snow experiment:
421 artificial deposition of light-absorbing particles onto snow surfaces in 2018, *Front.*
422 *Earth Sci.*, 12, 1358155, <https://doi.org/10.3389/feart.2024.1358155>, 2024.
- 423 Warren, S. G. and Wiscombe, W. J.: A model for the spectral albedo of snow. II: Snow
424 containing atmospheric aerosols, *J. Atmos. Sci.*, 37, 2734–2745, doi:10.1175/1520-
425 0469(1980)037<2734:AMFTSA>2.0.CO;2., 1980.
- 426 Weber, A. M., Beaudon, E., Sierra-Hernández, M. R., Davis, M., Kenny, D., Shutkin, T.
427 Y., and Thompson, L. G.: On the influence of mineral dust on glacial albedo at
428 Nevado Huascarán (Cordillera Blanca, Peru), *J. Geophys. Res.-Atmos.*, 131,
429 e2025JD045574, <https://doi.org/10.1029/2025JD045574>, 2026.
- 430 Yang, J., Kang, S., Chen, D., Duan, K., Wang, N., Du, W., Zhao, L., Deng, H., Wang, R.,
431 Zhang, Z., and Gillies, R. R.: Reduced solid water storage over the Tibetan Plateau
432 caused by black carbon, *Commun. Earth Environ.*, 6, 430,
433 <https://doi.org/10.1038/s43247-025-02335-9>, 2025.