Microplastics in a tropical Andean Glacier: A transportation process across the Amazon basin?

Article *in* Science of The Total Environment · September 2021

DOI: 10.1016/j.scitotenv.2021.150334

10 authors, including:

Marcela Cabrera
Universidad Regional Amazónica IKIAM
16 PUBLICATIONS **43** CITATIONS
SEE PROFILE

G. Moulatlet
50 PUBLICATIONS **531** CITATIONS
SEE PROFILE

Bryan Valencia
Universidad Regional Amazónica IKIAM
35 PUBLICATIONS **789** CITATIONS
SEE PROFILE

Bruno Conicelli
Universidad Regional Amazónica IKIAM
38 PUBLICATIONS **149** CITATIONS
SEE PROFILE

Science of the Total Environment 805 (2022) 150334

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

Microplastics in a tropical Andean Glacier: A transportation process across the Amazon basin?

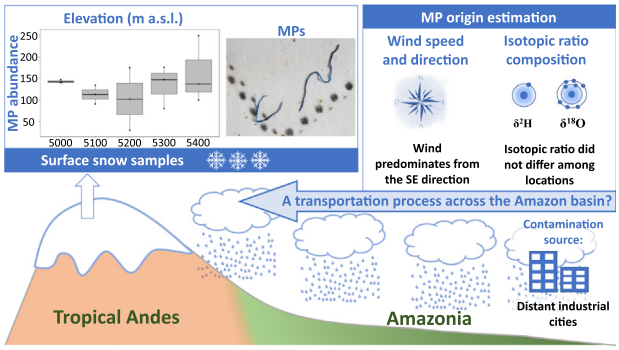
Marcela Cabrera [b], Gabriel M. Moulatlet [a], Bryan G. Valencia [a,g], Luis Maisincho [c,d], Rocío Rodríguez-Barroso [e], Gemma Albendín [e], Ayda Sakali [e], Oscar Lucas-Solis [a], Bruno Conicelli [a,g], Mariana V. Capparelli [f,*]

[a] Facultad de Ciencias de La Tierra y Agua, Universidad Regional Amazónica Ikiam, Km 7, Vía Muyuna, Tena, Napo, Ecuador
[b] Laboratorio Nacional de Referencia Del Agua, Universidad Regional Amazónica Ikiam, Ecuador
[c] Instituto Nacional de Metereología e Hidrología (INAMHI), Iñaquito, N36-14 y, Corea, Quito, Ecuador
[d] Insitut des Geosciences de L'Environnement (IGE, UMR 5001), 38000 Grenoble, France
[e] Facultad de Ciencias del Mar y Ambientales, Campus Universitario de Puerto Real, Universidad de Cádiz, Spain
[f] Estación el Carmen, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Carretera Carmen-Puerto Real km 9.5, C. P 24157 Ciudad del Carmen, Campeche, Mexico
[g] Grupo de investigación de Ciencias de la Tierra y Clima, Universidad Regional Amazónica Ikiam, Km 7, Vía Muyuna, Tena, Napo, Ecuador

HIGHLIGHTS

- Microplastic (MP) contamination was found in a tropical glacier at the Andes Mountains (above 5000 m).
- Polyurethane was the prevalent polymer type, which discard the possibility of MP origin from climbing clothing and equipment.
- Isotopic ratio composition and wind direction analysis indicate that air masses that travel over the Amazon.
- MP at the Antisana glacier are more likely to be transported over the Amazon than from Andean cities.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 July 2021
Received in revised form 9 September 2021
Accepted 10 September 2021
Available online 15 September 2021

Editor: Damia Barcelo

Keywords:
Surface snow deposition
Atmospheric transport
Contaminants
Antisana
Ecuador
Isotopes
Wind direction

ABSTRACT

Microplastic (MPs) contamination is ubiquitous in most terrestrial and aquatic ecosystems. Recently MPs have been reported at high altitudes which indicates that air masses can transport and deposit MPs in the surface snow of high mountain ecosystems, however, whether MPs typification and abundance can be influenced by direction and origin of air masses still remains an open question. Here we present the first report of MPs above 5000 m a.s.l from surface snow of a glacier in the tropical Andes. We collected surface snow along an elevational gradient, from 5000 to 5400 m a.s.l., in the Antisana Glacier, in the northern Andes cordillera of Ecuador to analyze MPs abundance and polymeric identification with the Fourier Transform Infrared (FTIR) and also to hypothesized the possible MPs sources in this remote area by comparing the oxygen and hydrogen stable isotopic ratio composition of the snow samples and by analyzing the wind direction. We observed an average of 131 ± 24 MPs L^{-1} in our samples. Fibers corresponded to 70% of all MP shapes; FTIR results showed that MPs composition mainly included polyurethane, polyethylene, polyamide, polyester, and high-density polyethylene in surface snow. There were no statistically significant differences of MPs abundance among sampled elevations, and the isotopic ratio composition did not differ among locations. Our results suggest that MP that accumulated in the glacier may be transported from the east, across the Amazonia, by the prevalent eastward air flow. The

* Corresponding author.
E-mail address: marivcap@gmail.com (M.V. Capparelli).

https://doi.org/10.1016/j.scitotenv.2021.150334

absence of industrial cities at least 2000 km further east from Antisana, indicates that the remote Andean glaciers could constitute important depositional zones for long-distance transported contaminants.

1. Introduction

Studies on MPs atmospheric deposition in glaciers remain scarce, and the magnitude of related environmental impacts of this contamination are yet to be assessed (Allen et al., 2019; Zhang et al., 2020). The sources of MPs in high-mountain ecosystems can be due to the breakout or degradation of large plastic items carried by expeditionists into smaller pieces through physical-chemical or biological processes (Parolini et al., 2021). However, recent studies demonstrated that atmospheric transport might be the main pathway of MPs to high-mountain environments, as observed in the ablation zone of the Forni Glacier (2580 m a.s.l, Italian Alps) (Ambrosini et al., 2019), in snow samples from Laohugou and Qiangyong Glaciers (Tibetan Plateau) (Zhang et al., 2021), in four high-mountains (2500 m a.s.l.) at Aosta Valley (Western Italian Alps) (Parolini et al., 2021), in Vatnajökull Ice Cap in Iceland (1400 m a.s.l.) (Stefánsson et al., 2021) and Mount Everest (Napper et al., 2020). Although the widespread occurrence of MPs in mountain ecosystems has been increasingly documented, tropical glaciers (above 4000 m a.s.l.) remain as sites where the occurrence and distribution of MPs, and the mechanisms of MPs transportation are still to be unraveled.

Glaciers are potential accumulation sites for other airborne contaminants, as glacier ice forms through the transformation of accumulated blizzards, which are particularly effective in removing atmospheric contaminants, including small debris (Ambrosini et al., 2019; Lei and Wania, 2004; Lovett and Kinsman, 1990). Thus, atmospheric MPs deposition in glaciers is quite likely, given that high elevation glaciers are exposed to the wind and to wet deposition (Allen et al., 2019; Klein and Fischer, 2019; Zhang et al., 2020). The atmosphere is an important pathway by which many suspended materials are transported regionally or globally. The size range for long-distance and even global transport of dust is <25 μm (Brahney et al., 2021). MPs are more transportable than dust and other soil particles (~2.65 g cm^{-3}) due to their small sizes and low densities (0.65 to 1.8 g cm^{-}) (Brahney et al., 2020; Liu et al., 2019). To the date, Andean glaciers represent a research gap in the global distribution of MPs and other contaminants, because accessing glacier accumulation zones is a challenge, as they are located in high elevation regions with rugged topography (Basantes-Serrano et al., 2016).

The tropical Andes, with mean summit elevations above 4000 m a.s.l. (Garreaud, 2009; Guy et al., 2019), play a significant role in controlling the weather and climate of South America (Sepulchre et al., 2009). The Andes form a significant barrier to eastern atmospheric flow since the Cenozoic (Guy et al., 2019; Insel et al., 2010). Thus, the prevalent precipitation events that reach eastern Andean glaciers in Ecuador come from air masses that collect moisture when transported over Amazonia. If the air masses coming from east are the main pathway of MPs transportation to Andean glaciers, long-distance MPs transportation should be assumed in opposition to short-distance transportation, considering that the nearest larger urban areas are located northwest from the glaciers. Short-distance MP atmospheric transportation could be associated with the transportation of contaminated air masses from the industrial and highly populated city of Quito, located 40 km at the northwest of the glacier; long-distance MP transportation, on the other hand, could be associated with the eastern air masses transported from Amazonia but that do not cross the barrier formed by the Andes.

The oxygen and hydrogen isotopic composition (δ18O and δ2H) of precipitation can be used to understand possible sources and transport mechanisms of MPs carried by air masses and further deposition in glaciers (Duan et al., 2016). For instance, the comparison between the Global Meteoric Water Line (GMWL) and the Local Meteoric Water Line (LMWL) allows the identification of moisture origins and precipitation processes at a particular locality (Wang et al., 2018). The isotopic variability is controlled by various factors: the temperature effect, the continentality effect, the moisture source effect, the amount effect, and the elevation effect (Pape et al., 2010). However, in the tropical highlands, the main factor driving isotopic variability is the elevation effect (Guy et al., 2019). The temperature drops of moist air-parcels uplifting against a mountain range produce heavy orographic rainfall with a prevalent depletion of the heavy isotope. The elevation effect changes the rainfall isotope composition from −0.15 to −0.5‰ per 100 m increase in elevation (Clark and Fritz, 1997). The isotopic profiles from four Andean glaciers have indicated that they relate to the precipitation variability over the Amazon basin (Guy et al., 2019; Hoffmann et al., 2003). This is because in eastern Ecuador, the precipitation comes from the Atlantic Ocean or recycled over the Amazon forests (Johnson, 1976; Hastenrath, 1981; Laraque et al., 2007). Then, the humid air masses from Amazonia are uplifted on the eastern Andes, producing orographic rainfall on the eastern slopes and a rain shadow on the leeward side slopes (Laraque et al., 2007).

MPs have been accumulating in glaciers in different mountain ranges across continents. However, the abundance, distribution and polymeric identification of MP pollution in surface snow samples have not been evaluated in Tropical glaciers to date. MPs were once reported in the Antisana glacier in the Andes of Ecuador (Cabrera et al., 2020), although the possible MPs sources were not discussed. MP atmospheric deposition indicates the ubiquitous presence of MPs in the air masses. Allen et al. (2019) reports MP atmospheric deposition from sources located 95 km from the glaciers, a distance range in which several urban areas can be found near our study site. Whether MPs are transported via atmospheric pathways to tropical glaciers from nearby sources or from faraway sources, as predicted by global atmospheric models (Evangeliou et al., 2020), remains an open question. Here, we evaluate the characteristics of MPs from snow deposition samples collected above 5000 m a.s.l at one glacier of the Antisana volcano, in the tropical Andes of northern Ecuador. By analyzing the isotopic ratio composition and the wind direction, we test the hypothesis of long vs. short distance transportation to discuss the possible origins of MPs to this remote area.

2. Methods

2.1. Study site and sample collection

This study was carried out in the glacier 15-α (0.478693°S, 78.147966°W, area ~ 0.71 km^2) of the Antisana Volcano (Fig. 1). That glacier was selected because it is the most studied and monitored outlet glacier on the Antisana ice cap (Cauvy-Fraunié et al., 2013). The Antisana Volcano (5753 m a.s.l) supports the largest and the fourth-highest ice cap of the Ecuadorian Andes (total surface area of the ice cap ~15 km^2 and elevation range 4870–5750 m a.s.l). Antisana is an irregular, cone-shaped stratovolcano located 40 km east of Quito (capital of Ecuador). Meltwater from Antisana glaciers provides part of the drinking water supply for Quito (Francou et al., 2004). Also, meltwater runoff supports the paramo wetlands, an essential highland ecosystem that provides several ecosystem services (Buytaert et al., 2006). Precipitation at the Antisana is bimodal, with enhanced rainfall from February to June and from September to November. The mean temperature at the proglacial margin (4850 m a.s.l.) ranges between 0 °C and 2 °C (Cauvy-

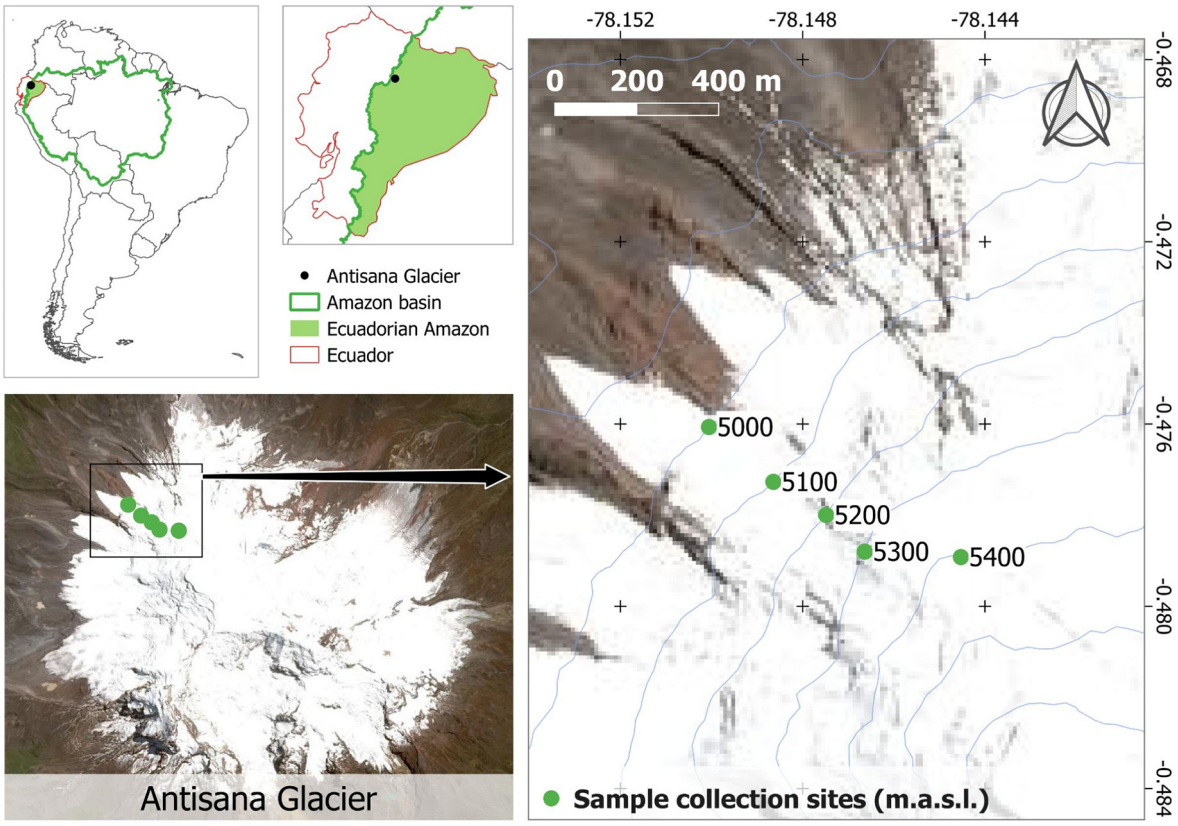


Fig. 1. Map of the study area indicating the Antisana glacier extension and the location of the sample collection sites (green dots). Topographic contour lines (blue lines) set every 100 m of elevation are shown in the right panel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fraunié et al., 2013). Few and scattered human populated areas lie around Antisana.

Surface snow sampling was carried out in February 2020. We collected a set of three independent surface snow samples, every 100 m, from 5000 to 5400 m a.s.l. At each sampling location we retrieve a consistent snow volume (450 mL), about 25 cm deep. While taking the surface snow samples, the mountaineering crew, trained to avoid MP contamination, remained downwind to the sampling points. Surface snow samples were collected with a metal sampler. Samples were transported in coolers filled with dry ice to avoid melting. The samples were stored in a freezer at −18 °C and analyzed at the National Water Reference Laboratory (NWRL) housed at Universidad Regional Amazónica Ikiam. The full description of the determination of sampling sites and sampling methodology is described in Cabrera et al. (2020).

2.2. Isolation and characterization of microplastics

During the isolation of MPs in the laboratory, only clothes made of natural fabric and clean lab coats were worn. Before usage, all laboratory materials were first rinsed with Milli-Q water and then with ethanol 98%. Blank samples were arranged during isolation and characterization of MPs. The blank samples consisted of Milli-Q water frozen at −18 °C and processed as the snow samples. The samples were processed in a laminar flow hood. The isolation of MPs was based on the methodology proposed by Cabrera et al. (2020). Surface snow and blank samples were melted at room temperature. Subsequently, a volume of 250 mL was filtered through 0.45 μm cellulose nitrate membranes with Ø = 47 mm (Pall Corporation), using a borosilicate laboratory glass vacuum filtration equipment. The membrane with the filtrate was rinsed into a graduated glass beaker with Milli-Q water. Then, a separation method was applied to isolate MPs particles from the inorganic material that prevents clear and accurate identification. 20 mL of Sodium Chloride (NaCl, 1200 kg m^{-3}) was added to the content of the glass and later the NaCl solution was filtered using a filter of 0.22 μm pore size (Millipore Whatman).

The samples were passed through 15 mL centrifuge tubes and centrifuged at 3000 rpm for 5 min to remove sediment particles. The supernatant was filtered for later visual quantification. Clean filter papers were placed in Petri dishes and exposed to room air in the laboratory during the quantification to account for possible atmospheric contamination. The filters were then analyzed, and the MPs found were subtracted from the total samples.

Filters were examined under an optical microscope (Motic BA 210E, 10×/0.25 zoom) by an experienced observer in the identification of MPs. All MPs particles were counted and classified into categories according to their shape (fragments, sphere, fibers, and films), as described by Crawford and Quinn (2017) and color. MPs ranged between 60 and 2500 μm were reported in this study.

A standard percentage (3%) of MP at each height was analyzed with Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) (PerkinElmer Spectrum 100™ FT-IR Spectrometer) to characterize the polymeric composition of the isolated items. The characterization was performed in reflection mode in a wavenumber range of 4000–650 cm^{-1} and scans were performed using a spectral resolution of 4 cm^{-1} and were executed in 16 scans (Primpke et al., 2018). In the analysis of the MPs, a spectral search was performed against a library of polymer spectra (FT-IR Polymer Resource Pack). A polymer was considered as such when the matching with the respective polymer in the library was >70%.

2.3. Isotope ratio composition and wind direction analysis

Isotopic ratios (δ^2H and $\delta^{18}O$) of surface snow samples were measured using a Triple Water Vapor Isotope Analyzer (LWIA – 45-EP; Los

Gatos Research Inc.), which is based on Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) technique. All isotopic values have been expressed in parts per thousand (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW).

Wind speed and wind direction data from a meteorological station that lies at the Antisana volcano (0.470381°S, 78.151183°W) at 4850 m a.s.l were provided by the Meteorological and Hydrological Institute of Ecuador (INAMHI). The data collection corresponds to the years 2019 and 2020. The temporal resolution for data measurements was 30 min. The station was inoperative for 22 h, starting at 12:30 pm on Jun the 1st. Data is unavailable during these 22 h. Wind speed and direction were analyzed using the R package bReeze (Graul & Poppinga, 2018).

2.4. Statistical analysis

The mean differences in the concentration of MPs isolated from surface snow collected at the five sampling sites were analyzed with pairwise Wicoxon signed-rank non-parametric tests and by applying the Bonferroni correction for multiple comparisons. The normality assumption was analyzed with Shapiro-Wilk tests and homoscedasticity with Levene's tests prior to the analyses. Significant differences were considered at p-value <0.05. The same analytical procedure was applied to detect mean differences between isotopic ratios. Statistical analyses were performed using the software R (R Core Team, 2020).

3. Results and discussion

3.1. MPs characterization

The highest concentration of MPs (Fig. 2a) was found at 5400 m a.s.l (162 ± 78 MPs L^{-1}), followed by 5000 m a.s.l (143 ± 3 MPs L^{-1}), 5300 m a.s.l (134 ± 49 MPs L^{-1}), 5100 m a.s.l (113 ± 22 MPs L^{-1}) and the lowest concentration was found at 5200 m a.s.l (102 ± 73 MPs L^{-1}). However, no statistically significant difference in MPs concentration among the five sites were found (p-values >0.05). The majority of the MPs particles included fibers (70%), films (15%), fragments (14%), and spheres (1%) (Fig. 2b). Overall, MPs were predominantly transparent (63%), but blue (15%), black (8%), white and red (7%) were also common colors. In each elevational belt, the proportions of colors were variable, although transparent was the most common color in every elevation (Fig. 2c).

Fibers were also the most common type of MPs reported in the Tibetan (Zhang et al., 2021), Alpine (Parolini et al., 2021) and Everest (Napper et al., 2020) glaciers. Maybe due to the greater surface area to

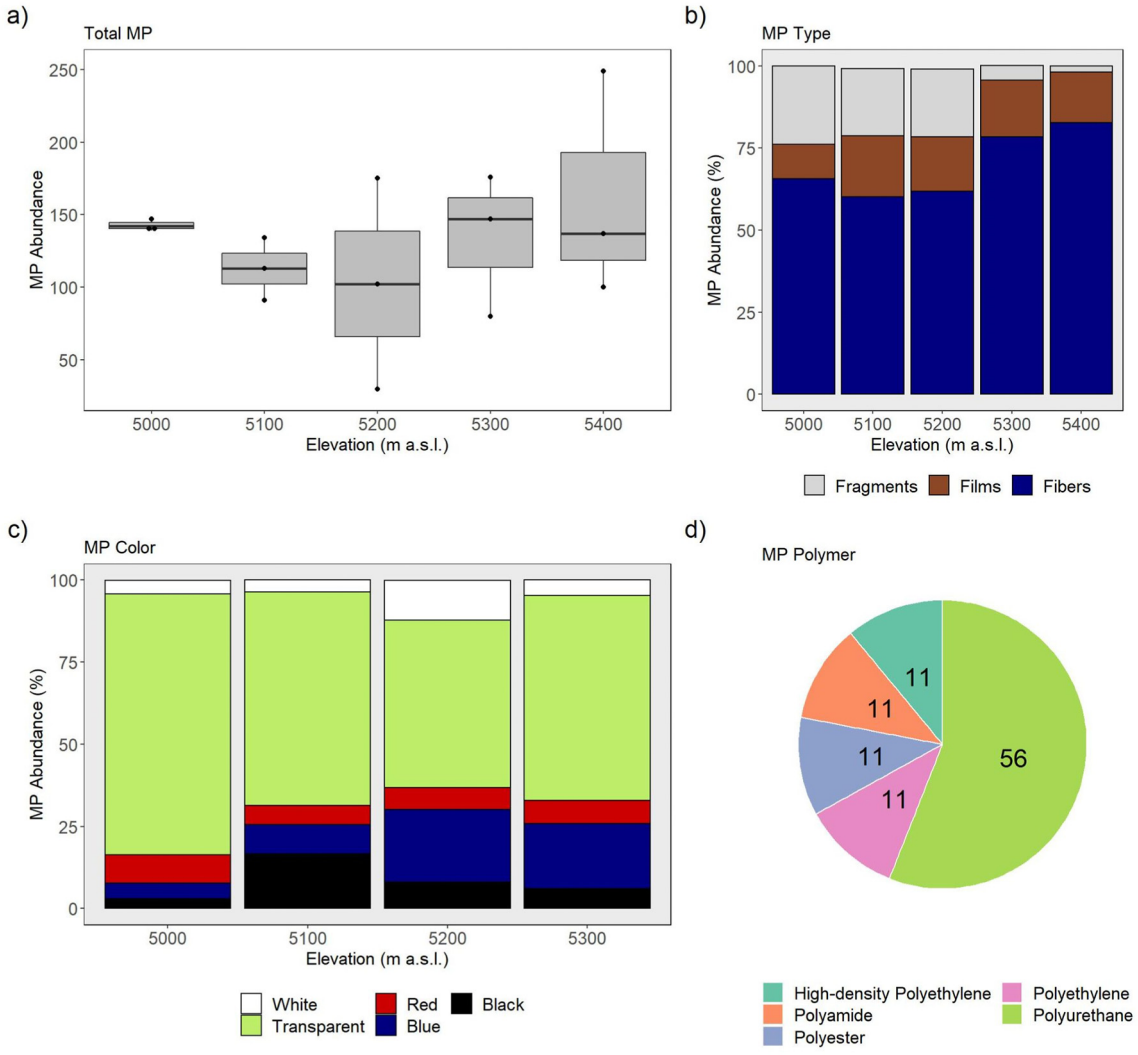


Fig. 2. a) Concentration of MPs (expressed in MPs L^{-1} of melted snow) in snow samples from the five altitudes in the Antisana Glacier. b) Number of microplastics (MPs) grouped by shape. c) Number of microplastics (MPs) grouped by color. d) Proportion of MPs polymeric types.

volume ratios, which increase drag forces and reduce settling velocity, fibers are found at higher proportion in high elevational deposition areas (Brahney et al., 2020). Regarding the color, studies conducted in other glaciers reported colored MPs as more abundant than transparent MPs. For instance, in the Tibetan glaciers black, red, green and blue MPs predominate (Zhang et al., 2021), while in one Alpine glacier black, blue, transparent and red were the common color types (Parolini et al., 2021). Transparent MPs can originate from packaging products such as plastic bags, cups, and bottles, which are disposable and have a short lifetime (Zhang et al., 2018). Xia et al. (2020) reported that transparent MPs were also predominant in surface water from relatively remote aquatic systems, while higher abundance of colored MPs was reported in urban areas affected by intense human activity.

The polymers identified in this study (Fig. 2d) included polyurethane (PU, 56%), polyethylene (PE, 11%), polyamide (PA, 11%), polyester (PS, 11%) and high-density polyethylene (HDPE, 11%). PU is used in coatings, adhesives, thermal insulation, furniture, mattresses, structural materials for automotive and building industry (do Canto et al., 2019). PS, acrylic, and PP are standard fibers for clothing. PS and nylon are also popular materials for tents and climbing ropes (Napper et al., 2020). This could explain the prevalence of PS (56%), acrylic (31%), nylon (9%), or PP (5%) in glaciers with intense climbing activity (Napper et al., 2020). In Alpine glacier, PE (39%) was the most abundant polymer, followed by PET (17%), HDPE (17%) and PS (11%) (Parolini et al., 2021). In Vatnajökull glacier, PU, polyvinyl chloride, PA, and acrylonitrile butadiene styrene (Stefánsson et al., 2021).

3.2. Isotopic precipitation ratio and wind direction

The stable isotope data for snow samples from the Antisana ranged from −15.75‰ to −13.63‰ for δ18O and from −113.45‰ to −98.75‰ for δ2H (Fig. 3). The deuterium excess was between 10.29‰ and 14.12‰. The isotope line from the Antisana samples was $\delta 2H = 7.017\ \delta 18O - 2.0947$ and overlapped with the local and regional meteoric water lines (LMWL: $\delta 2H = 8.33\ \delta 18O + 14.65$ and GMWL: $\delta 2H = 8\ \delta 18O + 10$, respectively). The LMWL was derived from the Ikiam meteorological station located in the Ecuadorian amazon at c. 600 m a.s.l (0.949524°S, 77.862796°W; Jiménez, 2020). Changes in

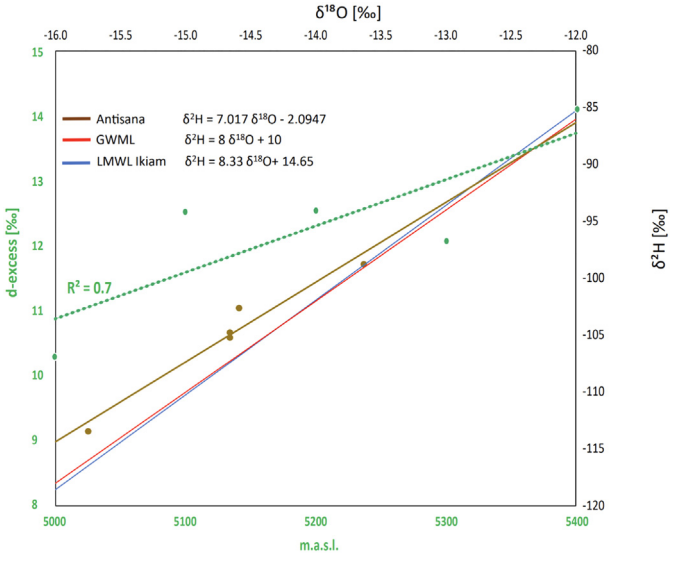


Fig. 3. Scatter plot of $\delta^{18}O$ and $\delta^{2}H$ and deuterium (d) excess. Isotopes lines from the Antisana (brown line) and Local Meteoric Water Line (LMWL) from the Ikiam station (blue line), located about 60 km Southeast of the Antisana, are plotted in relation to the Global Meteoric Water Line (GMWL, red line). The variation of deuterium excess along elevation is shown in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rainfall isotopic composition (fractionation) are influenced by the origin of air masses, elevation, continentality, and latitude. In addition, the isotopic composition is also affected by synoptic weather patterns in single precipitation events (Crawford et al., 2013; Tian et al., 2018). For the Antisana, the elevation is the most influential factor favoring heavy isotope depletion in rainfall. As an air parcel passes over an orographic barrier, like the Antisana, it is forced upward, reducing its temperature and favoring the preferential rainout and depletion of heavier isotopes (Dansgaard, 1964; Guan et al., 2009; Purdie et al., 2010). Another factor that explains the heavy isotope depletion is the continentality effect. The farther an air mass travels inland; the precipitation becomes more negative with a deficit in heavier isotopes (Dansgaard, 1964; Purdie et al., 2010).

Dansgaard (1964) established the deuterium as an indicator of the precipitation source region and/or variations at the source area (Araguás-Araguás et al., 2000; Jouzel et al., 2007; Purdie et al., 2010; Schwikowski et al., 2005). This allows tracking moisture source areas and air mass trajectories to improve our knowledge of regional climate systems and help to distinguish climate variability from climate trends (Jansson et al., 2007; Purdie et al., 2010). Deuterium changes seasonally, and usually, high values show a warm–dry source area and low values a cold–humid source area (Schwikowski et al., 2005; Purdie et al., 2010). The average deuterium detected in our samples (12.3‰) and values varying from 10.29‰ to 14.12‰ (Fig. 3) indicate that the moisture source may come from the Amazon. According to Salati et al. (1979), the deuterium of air masses that cross the Amazon remains in a range from 9.80 to 14.60 (‰), thus, corroborating our results.

The sample analysis from the Antisana supports the idea of a unique rainfall source given that deuterium gradually increases with elevation. A random variation of deuterium indicates multiple rainfall sources because the isotopic signatures change due to preferential rainout and air mass pathways (Dansgaard, 1964; Purdie et al., 2010). For instance, isotopic records from glaciers established on opposite sides of an orographic barrier show dissimilar isotopic concentrations, even when the snow originated from the same precipitation event (Purdie et al., 2010). Investigations in the Andes Mountains have confirmed that periodic changes in snow melting and evaporation rates can increase seasonal $\delta^{18}O$ profiles (Grootes et al., 1989; Lyn et al., 2004). Melting of the snow appears to have negligible effects on the deuterium values, although subsequent evaporation may change these values over diurnal and more prolonged timescales (Clark and Fritz, 1997; Lyn et al., 2004). In contrast, deuterium increases along the elevation gradient. A process consistent with an orographic uplift taking place over a side of the mountain (Guan et al., 2009). Therefore, the prevalent eastward air flow and a moisture transport trajectory that reaches the Antisana region dominate the studied site. This may explain why there is no significant difference in the number of microplastics found in the elevational gradient (5000–5400 m a.s.l).

Although urban centers may be the initial source of MPs (Brahney et al., 2020), the atmosphere can retain suspended particles over extended periods, allowing long-distance MP transport. The suspended MPs precipitate when air-mass velocities decline and with physical barriers, such as mountain chains. Then, the MPs transported by orographic precipitation are deposited in the glacier surfaces and might accumulate over time. The possible origin of MPs from performance clothing and equipment used by climbers, as identified by Napper et al. (2020) in Mount Everest is not plausible, as the Antisana is a remote destination rarely visited by climbers. Moreover, in situ MP contamination is also unlikely, as the most abundant microplastic type in our study was PU, a material generally absent in climber gears.

The prevalence of easterly airflow (Fig. 4) suggests that the Amazon basin is the primary source for moisture and MP reaching Antisana. This result is entirely consistent with the deuterium gradient enrichment that indicates a unique moisture source. Consequently, the large city of Quito, located 40 km NW from the Antisana glacier, is discarded as the primary MP source. The absence of any other large city on the

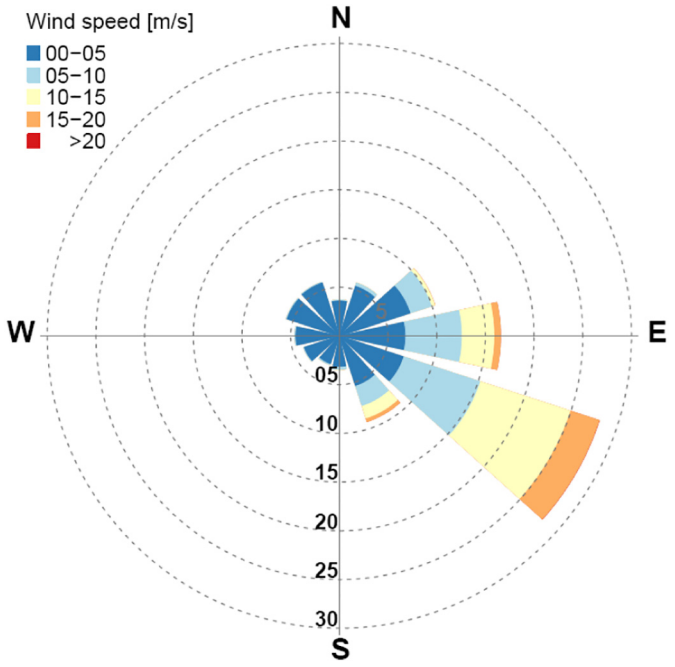


Fig. 4. Plot for wind speed and wind direction for years 2019 and 2020. The concentric bars depict the wind direction. Each bar was colored in proportion to the wind speeds registered in the depicted direction.

eastern side of the Antisana suggests that MP deposition results from long-distance atmospheric transport over the Amazon basin.

Although our data suggest long-distance MP transport, further sampling is needed to confirm the depositional processes for MPs in tropical glaciers. MPs trapped in the snow can persist on glaciers for an unknown amount of time. If the MP transportation pathway takes place over the Amazon basin, MP accumulation in tropical glaciers could trace back to the 1950s, a time when plastic waste was first released into the environment (Ambrosini et al., 2019). Long-distance deposition of MP particles in tropical glaciers like the Antisana implies in the contamination of tropical montane rivers such as the Amazon, as its headwaters are located in the tropical highlands that recieve meltwater from glaciers. Moreover, the persistence of MPs in glacier ice may reduce the snow and ice albedos, further exacerbating glacial melting (Kang et al., 2019).

The increasingly high rate of Antisana Glacier melting could result in increasing MP contamination in the downstream meltwater as glaciers recede, leading to an increasing concentration of MPs in the water consumed by the population of Quito (Donoso and Rios-Touma, 2020). For instance, the rate of current retreat appears to be unprecedented since the Little Ice Age (LIA) maximum that took place during the second half of the 17th century and the early 18th century (Rabatel et al., 2013). The consequences are not yet well understood, but the potential dangers posed by environmental MPs need to be evaluated and potentially mitigated.

4. Conclusion

Investigations on MPs atmospheric transportation and deposition are relatively new. Studies focused particularly on the breakdown, fate, and transport mechanisms of MPs in the atmospheric environment are particularly needed. Furthermore, research on the evaluation of the relationship between atmospheric MPs levels and meteorological conditions is required to fully understand the MPs transportation mechanisms (Can-Güven, 2021) and for long-distance transport modelling. Our findings of MP contamination above 5000 m a.s.l in a tropical Andean Ecuadorian glacier, demonstrated that this contaminant can reach remote, high mountain tropical areas. We were able, based on wind and isotopy data and MPs characterization, to show that the plastic accumulated in the glacier may be transported from the east, across the Amazonia basin, by the prevalent eastward air flow and a moisture transport trajectory. Due to the absence of large urban areas at least 2000 km further east from Antisana, Andean glaciers could constitute important depositional zones for contaminants transported over long continental distances.

CRediT authorship contribution statement

Marcela Cabrera: Writing – original draft, Conceptualization, Formal analysis, Data curation, Visualization, Project administration, Supervision. **Gabriel M. Moulatlet:** Writing – original draft, Formal analysis, Visualization, Investigation. **Bryan G. Valencia:** Conceptualization, Data curation, Writing – review & editing, Methodology, Project administration, Supervision. **Luis Maisincho:** Conceptualization, Investigation, Data curation, Formal analysis, Visualization. **Rocío Rodríguez-Barroso:** Conceptualization, Investigation, Methodology, Data curation, Writing – review & editing. **Gemma Albendín:** Conceptualization, Investigation, Methodology, Data curation, Writing – review & editing. **Ayda Sakali:** Methodology, Data curation. **Oscar Lucas-Solis:** Writing – original draft, Data curation, Visualization, Conceptualization, Investigation. **Bruno Conicelli:** Investigation, Writing – original draft, Formal analysis, Data curation, Visualization, Conceptualization. **Mariana V. Capparelli:** Investigation, Conceptualization, Data curation, Writing – review & editing, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are thankful to the crew of mountain climbers Carlos Alberto Paez, Luis Felipe Gualco, Orlando Vinicio Gutierres, Gustavo Adolfo Valarezo, Wilmer Guachamin Acero, Luis Maisincho Guagrilla, Evelyn Michelle Yambay, Miltón Perez, Gladys Cabascango, Juan Carvajal, Washington Chamorro (+), Yaryvic Coronel and the Ikiam driver Pablo Neris "Don Tito" Paz Andrade. This project was funded by European Union through the consortium AECID - Universidad Regional Amazónica Ikiam (CTC-004-2019, grant to BGV). We also acknowledge funding from the International Joint Laboratory GREAT-ICE, an initiative of the French Institute of Research for Development-IRD (leaders: Thomas Condom, IRD-France and Marcos Villacis, EPN, Quito Ecuador), French Glaciers Observatory Service-GLACIOCLIM (leader: Antoine Rabatel, Univ. Grenoble Alpes, CNRS-INSU, IRD, France) and INAMHI-Glacier Service (leader: Bolivar Caceres, INAMHI, Ecuador).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150334.

References

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12 (5), 339–344. https://doi.org/10.1038/s41561-019-0335-5.

Ambrosini, R., Azzoni, R.S., Pittino, F., Diolaiuti, G., Franzetti, A., Parolini, M., 2019. First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. Environ. Pollut. 253, 297–301. https://doi.org/10.1016/j.envpol.2019.07.005.

Araguás-Araguás, L., Froehlich, K., Rozanski, K., 2000. Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. Hydrol. Process. 14 (8), 1341–1355. https://doi.org/10.1002/1099-1085(20000615)14:8<1341::AID-HYP983>3.0.CO;2-Z.

Basantes-Serrano, R., Rabatel, A., Francou, B., Vincent, C., Maisincho, L., Cáceres, B., Galarraga, R., Alvarez, D., 2016. Slight mass loss revealed by reanalyzing glacier mass-balance observations on Glaciar Antisana 15α (inner tropics) during the 1995–2012 period. J. Glaciol. 62 (231), 124–136. https://doi.org/10.1017/jog.2016.17.
Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., Sukumaran, S., 2020. Plastic rain in protected areas of the United States. Science 368 (6496), 1257–1260. https://doi.org/10.1126/science.aaz5819.
Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., Prather, K.A., 2021. Constraining the atmospheric limb of the plastic cycle. Proc. Natl. Acad. Sci. 118 (16). https://doi.org/10.1073/pnas.2020719118.
Buytaert, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J., Hofstede, R., 2006. Human impact on the hydrology of the Andean páramos. Earth Sci. Rev. 79 (1–2), 53–72. https://doi.org/10.1016/j.earscirev.2006.06.002.
Cabrera, M., Valencia, B.G., Lucas-Solis, O., Calero, J.L., Maisincho, L., Conicelli, B., Massaine Moulatlet, G., Capparelli, M.V., 2020. A new method for microplastic sampling and isolation in mountain glaciers: a case study of one Antisana glacier, Ecuadorian Andes. Case Studies in Chemical and Environmental Engineering. 2, p. 100051. https://doi.org/10.1016/j.cscee.2020.100051.
Can-Güven, E., 2021. Microplastics as emerging atmospheric pollutants: a review and bibliometric analysis. Air Qual. Atmos. Health 14 (2), 203–215. https://doi.org/10.1007/s11869-020-00926-3.
Cauvy-Fraunié, S., Condom, T., Rabatel, A., Villacis, M., Jacobsen, D., Dangles, O., 2013. Technical note: glacial influence in tropical mountain hydrosystems evidenced by the diurnal cycle in water levels. Hydrol. Earth Syst. Sci. 17 (12), 4803–4816. https://doi.org/10.5194/hess-17-4803-2013.
Clark, I.D., Fritz, P., 1997. Environmental Isotopes in Hydrogeology. CRC Press Lewis Publishers, Boca Raton, FL.
Crawford, C.B., Quinn, B., 2017. Microplastic identification techniques. Microplastic Pollutants. Elsevier, pp. 219–267 https://doi.org/10.1016/B978-0-12-809406-8.00010-4.
Crawford, J., Hughes, C.E., Parkes, S.D., 2013. Is the isotopic composition of event based precipitation driven by moisture source or synoptic scale weather in the Sydney Basin, Australia? J. Hydrol. 507, 213–226. https://doi.org/10.1016/j.jhydrol.2013.10.031.
Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus 16 (4), 436–468. https://doi.org/10.1111/j.2153-3490.1964.tb00181.x.
do Canto, V.P., Thompson, C.E., Netz, P.A., 2019. Polyurethanases: three-dimensional structures and molecular dynamics simulations of enzymes that degrade polyurethane. J. Mol. Graph. Model. 89, 82–95. https://doi.org/10.1016/j.jmgm.2019.03.001.
Donoso, J.M., Rios-Touma, B., 2020. Microplastics in tropical Andean rivers: a perspective from a highly populated Ecuadorian basin without wastewater treatment. Heliyon 6 (7), e04302. https://doi.org/10.1016/j.heliyon.2020.e04302.
Duan, W., Ruan, J., Luo, W., Li, T., Tian, L., Zeng, G., Zhang, D., Bai, Y., Li, J., Tao, T., Zhang, P., Baker, A., Tan, M., 2016. The transfer of seasonal isotopic variability between precipitation and drip water at eight caves in the monsoon regions of China. Geochim. Cosmochim. Acta 183, 250–266. https://doi.org/10.1016/j.gca.2016.03.037.
Evangeliou, N., Grythe, H., Klimont, Z., et al., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nat. Commun. 11, 3381. https://doi.org/10.1038/s41467-020-17201-9.
Francou, B., Vuille, M., Favier, V., Cáceres, B., 2004. New evidence for an ENSO impact on low-latitude glaciers: Antizana 15, Andes of Ecuador, 0°28′S. J. Geophys. Res. 109 (D18), D18106. https://doi.org/10.1029/2003JD004484.
Garreaud, R.D., 2009. The Andes climate and weather. Adv. Geosci. 22, 3–11. https://doi.org/10.5194/adgeo-22-3-2009.
Graul, C., Poppinga, C., 2018. bReeze: functions for wind resource assessment. R package version 0.4-3. https://CRAN.R-project.org/package=bReeze.
Grootes, P.M., Stuiver, M., Thompson, L.G., Mosley-Thompson, E., 1989. Oxygen isotope changes in tropical ice, Quelccaya, Peru. J. Geophys. Res. Atmos. 94 (D1), 1187–1194. https://doi.org/10.1029/JD094iD01p01187.
Guan, H., Simmons, C.T., Love, A.J., 2009. Orographic controls on rain water isotope distribution in the mount lofty ranges of South Australia. J. Hydrol. 374 (3), 255–264. https://doi.org/10.1016/j.jhydrol.2009.06.018.
Guy, H., Seimon, A., Perry, L.B., Konecky, B.L., Rado, M., Andrade, M., Potocki, M., Mayewski, P.A., 2019. Subseasonal variations of stable isotopes in tropical Andean precipitation. J. Hydrometeorol. 20 (5), 915–933. https://doi.org/10.1175/JHM-D-18-0163.1.
Hastenrath, S., 1981. The Glaciation of the Ecuadorian Andes. A.A. Balkema Publishers 159 pp.
Hoffmann, G., Ramirez, E., Taupin, J.D., Francou, B., Ribstein, P., Delmas, R., Dürr, H., Gallaire, R., Simões, J., Schotterer, U., Stievenard, M., Werner, M., 2003. Coherent isotope history of Andean ice cores over the last century. Geophys. Res. Lett. 30 (4), 2002GL014870. https://doi.org/10.1029/2002GL014870.
Insel, N., Poulsen, C.J., Ehlers, T.A., 2010. Influence of the Andes Mountains on South American moisture transport, convection, and precipitation. Clim. Dyn. 35 (7–8), 1477–1492. https://doi.org/10.1007/s00382-009-0637-1.
Jansson, P., Linderholm, H.W., Pettersson, R., Karlin, T., Mörth, C.-M., 2007. Assessing the possibility to couple the chemical signal in winter snow on Storglaciären, Sweden, to atmospheric climatology. Ann. Glaciol. 46, 335–341. https://doi.org/10.3189/172756407782871459.
Jiménez, A.P.I., 2020. Variabilidad de isótopos estables del agua meteórica y percolada en la caverna de jumandy, Cuenca occidental del río Amazonas (Ecuador). Undergraduate thesisUniversidad Regional Amazónica Ikiam.
Johnson, A.M., 1976. In: Schwerdtfeger, W. (Ed.), The Climate of Peru, Bolivia, and Ecuador. World Survey of Climatology: Climates of Central and South America. Elsevier, pp. 147–219.
Jouzel, J., Stiévenard, M., Johnsen, S.J., Landais, A., Masson-Delmotte, V., Sveinbjornsdottir, A., Vimeux, F., von Grafenstein, U., White, J.W.C., 2007. The GRIP deuterium-excess record. Quat. Sci. Rev. 26 (1), 1–17. https://doi.org/10.1016/j.quascirev.2006.07.015.
Kang, S., Zhang, Q., Qian, Y., Ji, Z., Li, C., Cong, Z., Zhang, Y., Guo, J., Du, W., Huang, J., You, Q., Panday, A.K., Rupakheti, M., Chen, D., Gustafsson, Ö., Thiemens, M.H., Qin, D., 2019. Linking atmospheric pollution to cryospheric change in the third pole region: current progress and future prospects. Natl. Sci. Rev. 6 (4), 796–809. https://doi.org/10.1093/nsr/nwz031.
Klein, M., Fischer, E.K., 2019. Microplastic abundance in atmospheric deposition within the metropolitan area of Hamburg, Germany. Sci. Total Environ. 685, 96–103. https://doi.org/10.1016/j.scitotenv.2019.05.405.
Laraque, A., Ronchail, J., Cochonneau, G., Pombosa, R., Guyot, J.L., 2007. Heterogeneous distribution of rainfall and discharge regimes in the Ecuadorian Amazon Basin. J. Hydrometeorol. 8 (6), 1364–1381. https://doi.org/10.1175/2007JHM784.1.
Lei, Y.D., Wania, F., 2004. Is rain or snow a more efficient scavenger of organic chemicals? Atmos. Environ. 38 (22), 3557–3571. https://doi.org/10.1016/j.atmosenv.2004.03.039.
Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., Li, D., 2019. Consistent transport of terrestrial microplastics to the ocean through atmosphere. Environ. Sci. Technol. 53 (18), 10612–10619. https://doi.org/10.1021/acs.est.9b03427.
Lovett, G.M., Kinsman, J.D., 1990. Atmospheric pollutant deposition to high-elevation ecosystems. Atmos. Environ. Part A 24 (11), 2767–2786. https://doi.org/10.1016/0960-1686(90)90164-I.
Lyn, B., et al., 2004. Development of a Local Meteoric Water Line for South-eastern Idaho, Western Wyoming, and South-central Montana, Scientific Investigations Report 2004–5126, Idaho.
Napper, I.E., Davies, B.F.R., Clifford, H., Elvin, S., Koldewey, H.J., Mayewski, P.A., Miner, K.R., Potocki, M., Elmore, A.C., Gajurel, A.P., Thompson, R.C., 2020. Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. One Earth 3 (5), 621–630. https://doi.org/10.1016/j.oneear.2020.10.020.
Pape, J.R., Banner, J.L., Mack, L.E., Musgrove, M., Guilfoyle, A., 2010. Controls on oxygen isotope variability in precipitation and cave drip waters, Central Texas, USA. J. Hydrol. 385 (1), 203–215. https://doi.org/10.1016/j.jhydrol.2010.02.021.
Parolini, M., Antonioli, D., Borgogno, F., Gibellino, M.C., Fresta, J., Albonico, C., De Felice, B., Canuto, S., Concedi, D., Romani, A., Rosio, E., Gianotti, V., Laus, M., Ambrosini, R., Cavallo, R., 2021. Microplastic contamination in snow from Western Italian Alps. Int. J. Environ. Res. Public Health 18 (2), 768. https://doi.org/10.3390/ijerph18020768.
Primpke, S., Wirth, M., Lorenz, C., Gerdts, G., 2018. Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. Anal. Bioanal. Chem. 410 (21), 5131–5141. https://doi.org/10.1007/s00216-018-1156-x.
Purdie, H., Bertler, N., Mackintosh, A., Baker, J., Rhodes, R., 2010. Isotopic and elemental changes in winter snow accumulation on glaciers in the Southern Alps of New Zealand. J. Clim. 23 (18), 4737–4749. https://doi.org/10.1175/2010JCLI3701.1.
R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J.L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Wagnon, P., 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. Cryosphere 7 (1), 81–102. https://doi.org/10.5194/tc-7-81-2013.
Salati, E., Dall'Olio, A., Matsui, E., Gat, J.R., 1979. Recycling of water in the Amazon Basin: an isotopic study. Water Resour. Res. 15 (5), 1250–1258. https://doi.org/10.1029/WR015i005p01250.
Schwikowski, M., Brütsch, S., Palmer, A., Jenk, T.M., Gäggeler, H.W., Leuenberger, M., 2005. Identification of precipitation source regions at Fiescherhorn Glacier using the deuterium excess. Annual Report 2005. Paul Scherrer Institute Rep. Paper 27.
Sepulchre, et al., 2009. Modelling the response of Amazonian Climate to the uplift of the Andean Mountain Range. Book Chapter in: Amazonia: Landscape and Species Evolution: A Look Into the Past, by C. Hoorn and F. Wesselingh.
Stefánsson, H., Peternell, M., Konrad-Schmolke, M., Hannesdóttir, H., Ásbjörnsson, E.J., Sturkell, E., 2021. Microplastics in glaciers: first results from the Vatnajökull ice cap. Sustainability 13 (8), 4183. https://doi.org/10.3390/su13084183.
Tian, C., Wang, L., Kaseke, K.F., Bird, B.W., 2018. Stable isotope compositions (δ 2 H, δ 18 O and δ 17 O) of rainfall and snowfall in the Central United States. Sci. Rep. 8 (1), 6712. https://doi.org/10.1038/s41598-018-25102-7.
Wang, S., Zhang, M., Hughes, C.E., Crawford, J., Wang, G., Chen, F., Du, M., Qiu, X., Zhou, S., 2018. Meteoric water lines in arid Central Asia using event-based and monthly data. J. Hydrol. 562, 435–445. https://doi.org/10.1016/j.jhydrol.2018.05.034.
Xia, W., Rao, Q., Deng, X., Chen, J., Xie, P., 2020. Rainfall is a significant environmental factor of microplastic pollution in inland waters. Sci. Total Environ. 732, 139065. https://doi.org/10.1016/j.scitotenv.2020.139065.
Zhang, K., Shi, H., Peng, J., Wang, Y., Xiong, X., Wu, C., Lam, P.K.S., 2018. Microplastic pollution in China's inland water systems: a review of findings, methods, characteristics, effects, and management. Sci. Total Environ. 630, 1641–1653. https://doi.org/10.1016/j.scitotenv.2018.02.300.
Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., Sillanpää, M., 2020. Atmospheric microplastics: a review on current status and perspectives. Earth Sci. Rev. 203, 103118. https://doi.org/10.1016/j.earscirev.2020.103118.
Zhang, Y., Gao, T., Kang, S., Allen, S., Luo, X., Allen, D., 2021. Microplastics in glaciers of the Tibetan Plateau: evidence for the long-range transport of microplastics. Sci. Total Environ. 758, 143634. https://doi.org/10.1016/j.scitotenv.2020.143634.