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Weather stations on tropical glaciers: a multivariate dataset for cryospheric and climate research on Peruvian glaciers

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1 Introduction

Tropical glaciers serve as crucial sources of fresh water, particularly in arid tropical regions, where glacial runoff supports human consumption and economic activities such as agriculture, livestock farming, and tourism. Glaciers, due to their rapid response to melting conditions, are widely regarded as key indicators of climate change (Kaser and Osmaton, 2002). In recent years, a significant loss of glacier mass was reported along with changes in the climate of periglacial areas (ICCI, 2023); it was also estimated that the tropical Andean glaciers region has lost approximately 42% of its total area, with significant losses in regions below 5,000 masl in the 1990–2020 period (Turpo-Cayo et al., 2022), further alarming authorities and research workers due to its already discussed repercussions on other environmental and economic elements (Bradley et al., 2006; Kaser et al., 2005; Vergara et al., 2007).

In South America, the extent of glaciers covers several countries from Bolivia to Venezuela, with Peru having a large number of glaciers in its 18 glacial mountain ranges located mainly between the center and south regions. According to recent measurements, the total glacial extent was approximately 1050.32 km^2 as of 2020, representing a 6.5% reduction since 2017 (INAIGEM, 2023). Studies on the future of these glaciers indicate that smaller and low-lying glaciers in the tropical Andes are expected to disappear within a few decades under projected climate scenarios (Vuille et al., 2008). Recent studies suggest that the Cordillera Vilcanota could become mostly glacier-free by the end of the 21st century accompanied by an increase in the volume of glacial lakes in the near future (Drenkhan et al., 2018). In the Cordillera Huaytapallana, even under the most optimistic scenarios, glaciers are likely to disappear by 2050 (López-Moreno et al., 2014); the Cordillera Ampato has already experienced a 26.9% reduction in the glacier area, a trend largely influenced by large-scale circulation patterns such as ENSO and PDO phases, which also explain the maximum fluctuations observed in other tropical glaciers in the Andes (Rabatel et al., 2013; Kozhikkodan-Veettil et al., 2016; Lamantia et al., 2024).

Glacier retreat has been demonstrated to affect not only the dynamics of water supply and demand but also socioeconomic, environmental, and cultural systems, as discussed by several research workers (Salzmann et al., 2014; Zemp et al., 2015; Nussbaumer et al., 2017; Vuille et al., 2018; Condom et al., 2020); therefore, they highlight the importance of taking effective adaptive measures, taking into account that one of the challenges faced by decision-makers and research workers is the scarcity and availability of climatic, hydrological, *in situ* meteorological, and other necessary data as well as the need to create data-sharing systems and platforms to support the development of valid and quality information.

To address this issue, in this report, we present a database of four stations located in three Peruvian mountain ranges: Huaytapallana, located in the Cordillera of the same name Huaytapallana; Coropuna, in the Cordillera Ampato; Quelccaya and Quisoquipina, both situated in the same Cordillera called Vilcanota. These four stations have been recording hourly meteorological data for approximately 9–14 years, including variables such as air temperature, wind speed and direction, precipitation, humidity, and radiation, as detailed in the data description section. The data information presented has been processed and allowed to calculate daily, monthly, and annual averages/accumulation. This dataset has not yet been widely disseminated within the scientific community or the general public, and we hope it serves as a valuable resource for future research on tropical glaciers.

2 Value of the data

As stated, this dataset is being shared in order to deal with the scarcity of data in the tropics and high-elevation locations such as these four glaciers. The value of these data of more than 10 years lies in the great utility they have for the validation of satellite products and climate models, support for bias corrections, hydrological studies, glaciological studies, and specific topics such as energy balance and mass balance in tropical glaciers as there are stations in ablation and accumulation zones of the glacier.

3 Methods

3.1 Choice and description of the location of the weather stations

In 2011, the National Service of Meteorology and Hydrology of Peru (SENAMHI), through the Adaptation to the Impact of Rapid Glacier Retreat in the Tropical Andes Project (PRAA), financed by the World Bank's Global Environment Facility Fund, installed two weather stations to monitor meteorological variables related to glacier mass loss and to study climate variations in the region. The first one is in the Junin region on the front moraine of the Lazontay glacier in the Cordillera Huaytapallana at 4,700 masl, and the second one is in the Cusco region, on the Cordillera Vilcanota in the tongue of the Quisoquipina glacier at 5,180 masl, specifically in the ablation zone.

In 2014, SENAMHI, in cooperation with the Appalachia State University, installed a third station in the Cusco region, in the Cordillera Vilcanota at 5,560 masl, in the accumulation zone of the Quelccaya Ice Field; so, in this case, the purpose of this station is to monitor meteorological variables involved in accumulation processes. Since 2016, this station has also been part of the Global Cryosphere Watch network. A year later, in 2015, a fourth station was installed in the Cordillera Ampato in the Arequipa region at an altitude of 5,800 masl on the ablation zone of the Coropuna glacier plate tongue, which is the highest glacier volcano in the world.

Figure 1 shows the location of each station on the glacier images of Landsat-8 and the *in situ* automatic weather station equipment. The Quisoquipina station has a special design as it is located in the ablation zone of the glacier. In addition, considering that the glacier is constantly moving and that it cannot be visited more than once or twice a year, this station has been designed with a sensor stabilization system that allows maintaining an adequate perpendicular orientation of the radiation sensors to avoid obtaining erroneous data. The Coropuna station has a similar installation to the Quisoquipina station as it is also located in the ablation zone, so it has a stabilization system. Both stations have been installed because of the need to study the meteorological variables that are involved in the ablation process. This station was installed in cooperation with the Specialized Association for Development (AEDES), which is responsible for its operation and maintenance. The Quelccaya station, which is located in the accumulation zone near the mountain peak (5,610 masl), was installed to study the meteorological variables related to the process of snow accumulation on the glacier. This station is static and maintained once a year. It is worth mentioning that this station was transferred from the University of Appalachia to SENAMHI in 2022. These three stations are located in places that are difficult to be accessed, so it has been necessary to travel in vehicles for more than 4 h, walk for 2–3 h, and, in some cases, use horses to reach them. On the other hand, the Huaytapallana station was installed outside the glacier, and it only presents security risks and, thus, is protected by metal fences; however, the other three stations, being located on the glacier, required special conditioning considering the glacier movement, frequency of visits to the station, and security (access and theft).

3.2 Description of the variables and sensor types

The four stations record data on the variables recommended for CryoNet stations, specifically those related to surface meteorology (Global Cryosphere Watch, 2024): air temperature, air humidity, wind speed and direction, air pressure, precipitation, short- and long-wave radiation, and albedo; the Coropuna station also includes an ice surface temperature sensor. Data are recorded at hourly intervals and transmitted *via* satellite to SENAMHI headquarters.

Regarding the variables for glacier monitoring purposes, air temperature serves as an indicator of melting conditions if values are greater than or equal to 0 (≥0°C) and could also be used to compute the sensible heat flux, and air humidity was used to compute the latent heat flux. Wind speed is usually used to compute the sensible and latent heat flux; meanwhile, wind direction demonstrates the occurrence of katabatic winds. The albedo of a surface also determines the amount of heat reflected by that surface. It is an essential parameter for understanding the thermal balance of a surface exposed to solar radiation in the field of thermal comfort, climatology, and spacecraft.

Table 1 shows a list of equipment models for each station per variable; meanwhile, details such as its range and accuracy are attached as supplementary information. The Coropuna and Quisoquipina stations have a special structure consisting of a special tripod that allows keeping the radiation sensors in a

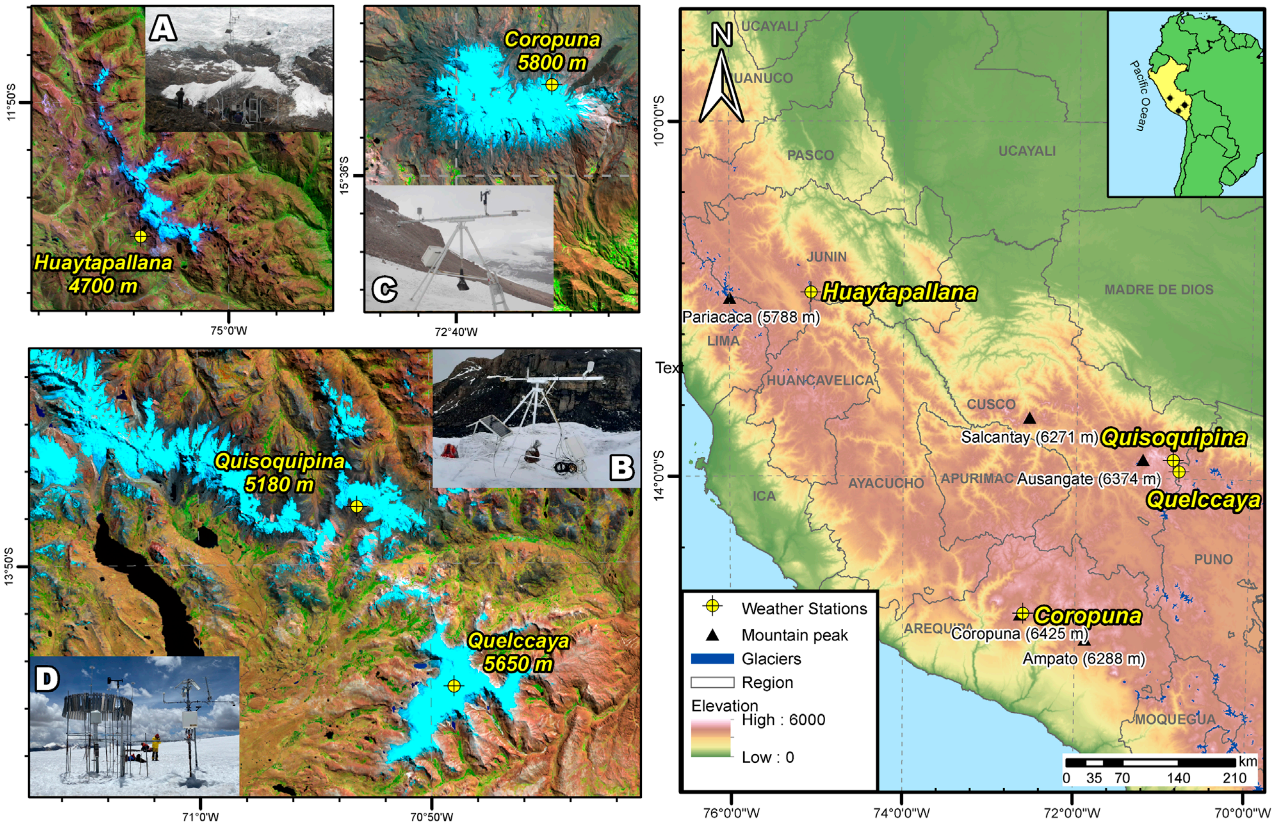

FIGURE 1
Location map of the automatic weather stations on glaciers: **(A)** Huaytapallana, **(B)** Quisoquipina, **(C)** Coropuna, and **(D)** Quelccaya. The respective elevations in meters of the stations and the mountain peaks are marked.

horizontal position (short- and long-wave radiation incident perpendicularly) while moving due to the effect of mass loss in the ablation zone. At both stations, radiation measurements are taken using a Kipp & Zonen CNR-1 Net Radiometer (later replaced by the CNR-4 model during the period 2017–2018); this instrument consists of two pyranometers and two pyrgeometers, arranged in pairs—one facing upward and the other downward—to monitor incoming and outgoing short-wave (albedo) and long-wave (heat flux) radiation. CNR-1 was replaced by the CNR-4 net radiometer because it is an improved version with a well-performing sensor, as demonstrated by Dou et al. (2015). On the other hand, it is worth mentioning that the sensors have not been observed to be covered by snow during maintenance visits to the stations.

3.3 Data processing

The raw dataset was collected as an Excel file and subsequently cleaned using Python libraries. First, values such as −999.9, NA, or non-numeric entries were deleted. Then, a second filter was applied to eliminate values outside the plausible limits, as outlined in SENAMHI's (2022) quality control guidelines:

Air temperature: $-40°C \leq T \leq 60°C$.

Relative humidity: $0.0 \leq RH \leq 100\%$.

Precipitation: $0 \leq PP \leq 401$ mm/h.

Wind speed: $0 \leq WS \leq 75$ m/s.

Wind direction: $0° \leq WD \leq 360°$.

Atmospheric pressure: 300 hPa $\leq P \leq 1{,}100$ hPa.

Incoming short-wave radiation: $-1 \leq SRin \leq 1{,}400$ W/m^2.

Albedo: $0 \leq Alb \leq 1$.

We also evaluated the time consistency and internal consistency of the parameters. Following a diurnal and seasonal boxplot analysis, an outlier detection process was applied to evaluate the "outer fences," defined by Turkey (1977) as Q1 (lower quartile) − 3*IQR (inter-quartile range) and Q3 (upper quartile) + 3*IQR. Based on this evaluation, we decide whether or not to discard these outliners. Radiation variables were processed according to their specific physical characteristics. For short-wave radiation components (outgoing and incoming) and albedo, values are expected to be non-null for 12 values per day from 11:00 to 23:00 UTC, which is the average daylight period in local time (6 a.m. to 6 p.m.). Therefore, the values outside this range were replaced with 0. Furthermore, outgoing values must be lower than incoming values; however, there are many hours (6% of total data) at the Coropuna station—particularly near sunset—where this does not happen. This may be related to residual radiation trapped in snow penitents, which are characteristic of glaciers in arid areas, as described by Lliboutry (1954) and Corripio and Purves (2005). On the other hand, for long-wave radiation, the outgoing component

TABLE 1 Station location details and model brand sensors per variable of each station.

Station	Quisoquipina	Quelccaya	Huaytapallana	Coropuna
Region	Cusco	Cusco	Junin	Arequipa
Cordillera	Vilcanota	Vilcanota	Huaytapallana	Ampato
Longitude	70°53′8″W	70°48′59″W	75°3′42″W	72°35′59″W
Latitude	13°47′34″S	13°55′11″S	11°55′38″S	15°32′10″S
Altitude	5,180 m	5,650 m	4,700 m	5,800 m
Glacier zone	Ablation zone	Accumulation zone	Outside of the glacier	Ablation zone
Variables	Sensor per variable			
Wind speed and direction	Young 05103-45	Young RM-Young 5	Young 05103-45	Young 05103-45
Temperature and relative humidity	Vaisala HMP45C	Vaisala	Vaisala HMP45C	Rotronic HygroClip 2
Atmospheric pressure	Vaisala PTB110	-	-	Vaisala PTB110
Radiation	KIPP & ZONEN: CNR1 (until 2016) CNR4 (since 2017)	-	-	KIPP & ZONEN: CNR1 (until 2018) CNR4 (since 2019)
Precipitation	-	OTT Pluvio^2	Texas Electronics TE552	-
Ice surface temperature	-	-	-	Apogee Instruments SI-111

can be greater or less than the incoming values, and outgoing long-wave radiation values can reach up to 316 W/m^2 when temperature values are ≤0°C. Values exceeding this limit were replaced with the respective threshold. We also evaluated the radiation values using additional processing procedures adopted in snow-covered stations, following approaches by Nishimura et al. (2023) and Wang et al. (2018). Finally, we calculated short-wave net radiation, long-wave net radiation, and total net radiation as the sum of their respective components.

4 Data description for each station

This dataset is a compilation of hourly measurements from the four weather stations presented as a daily mean or cumulative sum (in the case of the precipitation variable) in Figure 2; the start time of data recording is different for each station according to its date of installation.

4.1 Quisoquipina station

The Quisoquipina station has the largest amount of data among the four stations; it has recorded hourly data from 28 September 2011 until 12 July 2024 (with missing values between 2017 and 2019) for the following variables: air temperature, relative humidity, and wind speed and direction. Radiation variables were recorded as incoming and outgoing short-wave radiation, with averages of 463.64 W/m^2 and 256.59 W/m^2, respectively. Since 2018, there was a generalized increase in these variables, probably due to the radiation sensor change. Furthermore, long-wave radiation values were also recorded, with average incoming and outgoing components of 269.29 W/m^2 and 308.69 W/m^2, respectively. From these variables, we calculated the short-wave net radiation, long-wave net radiation, and total net radiation. Finally, albedo values were analyzed, with 0.59 as the total average.

4.2 Quelccaya station

The Quelccaya station, located at the second highest elevation, recorded hourly data for seven variables from 15 October 2014 until 11 October 2023 (with most missing values between 2015 and 2016). These variables include air temperature, relative humidity, and wind speed and direction data (average wind speed of 3.67 m/s, with southeastern winds being the most frequent), and the maximum wind speed is also recorded. Finally, in contrast to the previous stations, this one records hourly precipitation values, with a maximum cumulative daily sum of 34.49 mm.

4.3 Huaytapallana station

The Huaytapallana station recorded hourly data of five variables from 26 August 2013 until 2 July 2024 (most missing values in 2015). These variables include air temperature, relative humidity, and wind speed and direction, with an average speed of 1.85 m/s and mostly

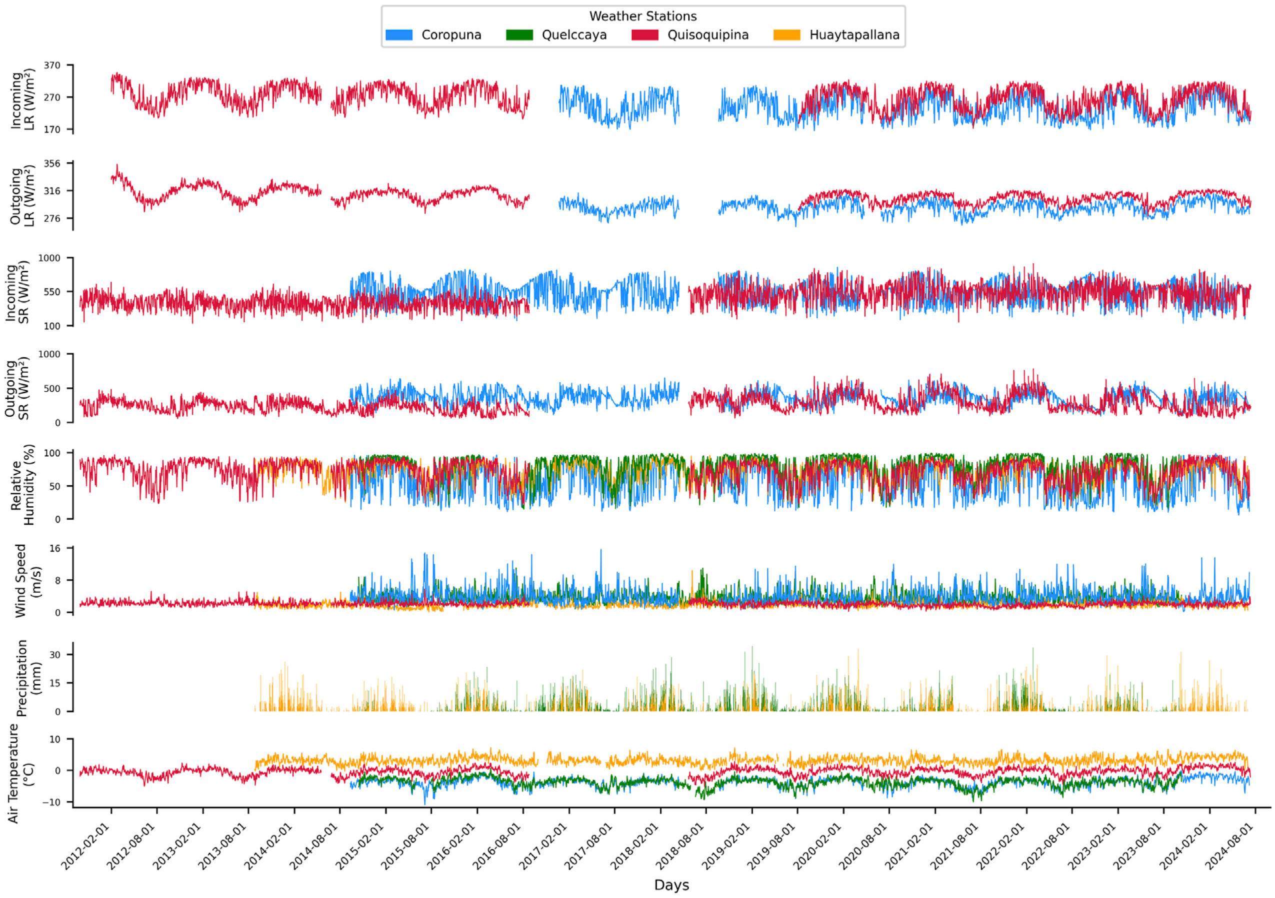

FIGURE 2
Time series of daily weather data measured at the four stations from 2011 to 2024. The variables are shown from top to bottom as follows: incoming long-wave radiation (W/m^2), outgoing long-wave radiation (W/m^2), incoming short-wave radiation (W/m^2), outgoing short-wave radiation (W/m^2), relative humidity (%), wind speed (m/s), accumulated precipitation (mm), and air temperature (°C).

northerly winds. In addition, precipitation values reach 32.98 mm of the cumulative daily sum.

4.4 Coropuna station

The Coropuna station recorded hourly data from 10 September 2014 until 9 July 2024, with missing values in 2018 and 2020. This station is the second in terms of the number of recorded values but with the most amount of variables, which include atmospheric pressure measured in hPa unit, air temperature (hourly maximum and minimum), relative humidity, and wind speed and direction; the wind speed values from this station are the highest (3.81 m/s as average) among all other stations, which corresponds to its location at the highest elevation. Meanwhile, the most frequent wind direction is from the south. This station also recorded solar radiation data, such as outgoing and incoming short-wave radiation; the calculated average values of these variables are 330.72 W/m^2 and 525.01 W/m^2, respectively; incoming and outgoing long-wave radiation had averages values of 238.15 W/m^2 and 291.93 W/m^2, respectively. Based on these, short-wave and long-wave net radiation and total net radiation were calculated. Other variables such as ice surface temperature were also recorded exclusively at this station.

5 Prospects for the future of the weather stations

SENAMHI is currently planning to operate the stations as part of a cryosphere observation network, which will be proposed for inclusion in the Cryonet network operated by the WMO. In addition, efforts are underway to standardize data acquisition procedures as the current framework are different for each station.

Data availability statement

The daily, monthly and annual cleaned datasets are available at: https://doi.org/10.5281/zenodo.15313382. The hourly cleaned and raw data can be obtained on request from the corresponding author via email.

Author contributions

WS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft. LC: Data curation, Formal Analysis, Visualization, Writing – original draft. MV: Data curation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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