

Weather station data from the Mount Everest region, Nepal: 3,810-8,810 m above sea level

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Abstract

Between 2019 and 2025, as part of the National Geographic and Rolex Perpetual Planet Everest expeditions, a team of National Geographic Explorers, scientists, and elite climbing Sherpas installed a network of Automatic Weather Stations (AWSs) to improve understanding of the climate at high altitudes in the Nepal Himalaya. This knowledge is critical in the Mount Everest (Khumbu) region, due to its extreme altitude, popularity amongst trekkers and mountaineers, and its importance as a source of freshwater for downstream communities. Here we present quality controlled (QC) meteorological data from six AWSs extending from Phortse (3,810 m above sea level, m asl) to Bishop Rock (8,810 m asl) in the Everest region, including the seasonal climatology focused on the three lower elevation AWSs, and a comparison with ERA5 reanalysis data from the South Col AWS. The data is accessible from <https://doi.org/10.5281/zenodo.18849098> (Khadka, 2026).

1. Introduction

Field research in High Mountain Asia (HMA), which contains the largest glacierized area outside of the polar regions (Brun et al., 2017; Pfeffer et al., 2014), is extremely difficult. The region's high elevations result in low barometric pressure (and hence relatively low oxygen availability: Matthews et al., 2020a), and extreme weather, challenging both personnel and equipment during the assembling of high-quality, long-term observational datasets (Salerno et al., 2015; Shea et al., 2015; Khadka et al., 2022; Matthews et al., 2020a). However, there are strong incentives to overcome these difficulties. First, the region is an important freshwater source for communities downstream (Immerzeel et al., 2010). Second, the extreme weather, combined with steep terrain, places the region at a relatively high risk of hydrometeorological hazards (Miner et al., 2020). Establishing meteorological observation networks both helps improve understanding of water resource availability under a changing climate and supports the reduction of hydrometeorological risks.

Within HMA, the Khumbu region has attracted significant cryospheric research interest (Salerno et al., 2015; Perry et al., 2020; Wagnon et al., 2021; King et al., 2020; Thakuri et al., 2014, 2019; Sherpa et al., 2023; Potocki et al., 2022). Its extreme elevation, comprising the highest (Mount Everest) and fourth-highest (Lhotse) mountains on earth, as well as the highest-elevation glacier combined with its thriving tourism and mountaineering industry, enable altitudinal gradients in meteorological quantities to be assessed across the entire elevational range of HMA glaciers; drive high demand for accurate weather observations and forecasts (due to the high exposure of trekkers and mountaineers); and provide relatively strong logistical support for fieldwork.

Compared to elsewhere in HMA, the Khumbu region has already been relatively well instrumented with automatic weather stations (AWSs). For instance, an AWS was deployed at Pyramid (5,035 m asl) by EvK2CNR in 1994, and their network was later extended up to South Col (in 2008) (Salerno et al., 2015, 2025). In 2010, the French National Research Institute for Sustainable Development (IRD France; GLACIOCLIM) and Nepalese partners began long-term weather measurements at Mera glacier up to 6,352 m asl and up to 5,450 m asl along the Changri Nup glacier nearby Khumbu Glacier (Figure 1; Khadka et al., 2022). On Everest's northern slopes, AWSs were installed at the North Col (7,028 m asl) and Ruopula Pass (6,560 m asl) (Yang et al., 2011) though these ceased operation by 2008 and 2010, respectively. More recently, Chinese scientists reportedly installed eight AWSs up to near the summit but these data remain unpublished (The Himalayan Times, 2022) and the state of the network remains unknown.

Despite significant investments by numerous research groups, critical gaps persist in understanding HMA cryospheric processes, climate change signals, and data dependability. Weather forecasts for peaks above

6,000 m asl, which can have life-or-death consequences for mountaineers, also remain highly uncertain because of lack of ground-based observations for validation (Matthews et al., 2020a). Furthermore, a scarcity of high-quality, elevation-dependent datasets hinders efforts to refine regional climate models and downscale reanalysis products, which is necessary to understand longer-term, larger-scale climate change in this region (Khadka et al., 2022).

During the 2019–2025 period, our team of researchers installed and maintained AWSs in six different locations along Everest’s southern slopes as part of the National Geographic and Rolex Perpetual Planet Everest Expeditions. These stations have since generated novel insights, including: seasonal oxygen availability at high elevations and climate-influenced changes in Everest’s physiological summit height (Matthews et al., 2020b); sublimation dynamics at South Col Glacier (Sherpa et al., 2023); seasonal variability in cloud cover and visibility (Grey et al., 2022); extreme solar irradiance patterns (Matthews et al., 2020a); energy balance studies (Matthews et al., 2020a; Potocki et al., 2022; Brun et al., 2023); and monsoon behaviour at extreme altitudes (Perry et al., 2020; Khadka et al., 2021).

In this paper, we focus on describing the latest available open-access data (<https://doi.org/10.5281/zenodo.18849098>; Khadka, 2026). We first provide a summary of the network (Section 2), before outlining quality control (QC, Section 3). We conclude by summarizing the seasonal climatology at stations with the most complete records (Section 4), the correspondence between South Col AWS observations and ERA5 (Section 5), and by sharing new insights from the highest stations with more intermittent records.

2. Observation area and data

The geographical locations of the different AWSs are shown in Figure 1. The five stations were initially installed in the primary Khumbu valley from Phortse (3,810 m asl; hereafter PH), Base Camp (5,315 m asl; hereafter BC), Camp II (6,464 m asl; hereafter CII), South Col (7,945 m asl; hereafter SC), and Balcony (8,430 m asl; hereafter BA) during the 2019 expedition (Matthews et al., 2020a). The BA station was toppled by extreme winds and anchor failure in January 2020, so in May 2022 a team of researchers and Sherpas returned to install a new AWS at Bishop Rock (8,810 m asl; hereafter BR), remove the BA station, and upgrade the SC AWS (Matthews et al., 2022).

Data have been recorded using Campbell Scientific CR1000X dataloggers, at intervals ranging from 10 minutes to daily. However, here we present quality-controlled hourly datasets in Coordinated Universal Time (UTC). The respective variables and sensors include air temperature (T), relative humidity (RH), wind speed (WS), radiation variables (incoming (in) and outgoing (out) shortwave (SW) and longwave (LW) radiation), pressure (p), and precipitation (P) (Table 1). We also include data from experimental pitot wind sensors installed at the SC and BR in 2022.



Figure 1. Geographical location of different automatic weather stations installed during the 2019-2022 National Geographic (NGS) and Rolex Perpetual Planet Everest expeditions, together with operational EvK2CNR and GLACIOCLIM stations in the Khumbu region of Nepal. Black symbols indicate the National Geographic Society AWSs, while the other symbols indicate EvK2CNR and GLACIOCLIM stations. Plus signs indicate important locations and camps, including Everest Base Camp. Changri Nup indicates the area where meteorological and glaciological observations have been conducted since 2010. The red line shows the standard climbing route to Mount Everest from the southern, Nepali side.

2.1 AWS details and measured variables

Two types of tripods were used for the AWSs: the Campbell Scientific CM106B, which has an adjustable height of between 2.1 and 3 m, was used for the lower three (PH, BC, and CII) AWSs. The tripod was affixed with a datalogger box, solar panel, various sensors and a grounding rod and lightning-protection system (Table 1, Figures S1 and S2). An OTT HydroMet Pluvio² with a double-Alter shield was installed separately at the PH and BC AWSs to measure precipitation. For the upper three (SC, BA and BR) AWSs, a 7-kg custom aluminum tripod designed by Campbell Scientific specifically for Everest was used (Matthews et al., 2020a). The PH and BC AWSs were secured in the soil with stakes pushed 0.5–1 m into the ground, while the higher elevation AWSs were bolted to rocks and also guyed to additional anchor points. For the lower elevation AWSs (PH, BC, and CII; < 6,500 m asl), the batteries were housed within the datalogger box enclosure mounted on the tripod. For the upper elevation AWSs (SC, BA, BR; > 6,500 m asl), the batteries were installed in a separate insulated box to provide protection from very low temperatures. Both the datalogger and battery boxes were separately bolted to the rock to reduce wind drag on the tripod. The overall weight of the lower elevation AWSs is approximately 60 kg and the upper elevation AWSs weigh 52 kg, including the additional pitot tube (~2 kg) and other sensors added in 2022 (Matthews et al., 2020a, 2022). The BA AWS was found to have been toppled during the 2020 maintenance visit, possibly

due to extreme wind gusts; however, the other tripods remain in position at the time of writing. Below, we provide measurement details for the respective meteorological variables. This information is also summarised in Table 1.

2.1.1 Air Temperature and Relative Humidity

Air temperature (°C) and relative humidity (%) were measured using a Vaisala HMP155A-L5-PT sensor installed in a naturally ventilated METSPEC 14-plate solar radiation shield. Additionally, a CS109 temperature probe, ventilated by a METSPEC 6-plate solar radiation shield, was installed for air temperature measurement at each station in 2019. While both shield types reduce radiative heating, the absence of active aspiration, particularly for the less protected CS109 with its six-plate shield may introduce a positive diurnal temperature bias. In 2022, however, only dual Vaisala HMP155A-L5-PT sensors with METSPEC 14-plate solar radiation shields were installed in the SC and BR AWSs. The sensors were installed 2 m from the ground for the lower elevation AWSs (PH, BC, and CII), and 1.5 m for the higher elevation AWSs. We chose a lower height for the high-altitude stations to protect them from strong winds in two ways. First, wind speeds are generally lower closer to the ground. Second, a shorter pole creates less leverage (torque) on the tripod base, which reduces the risk of tripod failure during severe wind gusts.

2.1.2 Wind Speed and Direction

Initially, in 2019, the R. M. Young 05108-45 anemometers were used at all AWSs for measuring wind speed and direction. The SC and BA AWSs were each equipped with two sensors for redundancy. However, all four R. M. Young 05108-45s failed in the extreme conditions encountered at the BA and SC. We therefore replaced the two 05108-45s at the SC with a new polycarbonate version of that sensor; we also added a Richards C5C anemometer and Pitot tube, custom made by the Mount Washington Observatory. This same sensor array for measuring wind speed was used at the BR station following the failure of the BA AWS (Matthews et al., 2022). All wind sensors were installed 2.3 m above the ground surface for lower AWSs (PH, BC, and CII) and ~2 m for higher elevation AWSs (SC, BA, and BR).

2.1.3 Air Pressure

The barometric air pressure (hPa) at PH was measured using a Vaisala PTB110, whereas the Vaisala PTB210 was used at the other AWSs because of the lower barometric air pressure at higher elevations. At all stations, the pressure sensors were housed inside the datalogger enclosure. At the three lower-elevation AWSs (PH, BC, and CII), the enclosure was mounted approximately 1–1.5 m above the ground.

2.1.4 Radiation

The four radiation components were measured using paired Hukseflux SR30 pyranometers for incoming and outgoing shortwave radiation and paired Hukseflux IR01 pyrgeometers for incoming and outgoing longwave radiation at PH. An Apogee SN-500-SS net radiometer was used at CII, while Hukseflux NR01 net radiometers were used at the other AWSs. The instruments were mounted on crossarms approximately 1.5 m above the surface (Figures S1 and S2).

2.1.5 Precipitation

Weighing OTT Pluvio² precipitation gauges equipped with double-Alter wind shields with a height of 1.5 m (from the surface at the mouth of Pluvio) were installed at the PH and BC AWSs. At both sites the OTT Pluvio² were partially filled with an environmentally friendly antifreeze solution, which is replaced regularly when the reservoir is emptied during regular maintenance visits. An optical disdrometer (OTT Parsivel²) and a snow-level sonic sensor (SR50A) were installed to complement the precipitation measurements. These datasets are included in the data archive but are not analysed in the present study because they require specialised quality-control procedures, including the removal of artefacts caused by wind and blowing snow (Table 1; Löffler-Mang and Joss, 2000; Ryan et al., 2008; Pérez-Tello et al., 2026). These datasets will be analysed in future work.

2.1.6 Time Lapse Photo

In addition to the meteorological measurements at the BC AWS, a Campbell Scientific CCFC field camera was installed facing east towards the summit of Mount Everest. The camera captures photographs two times a day; at 0937 Nepal time (NPT) (0352 UTC) and at 1437 NPT (0852 UTC), respectively (Grey et al., 2022).

2.2 Real-time data transfer

At the beginning of the project in 2019, all stations except PH were configured to transmit real-time data using the Thuraya satellite network, whereas the PH station used Inmarsat telemetry. Data transmission from PH ceased following a battery failure in September 2024. Separately, the failure of the Thuraya 3 satellite in April 2024 caused increasingly intermittent connectivity at the stations using Thuraya, followed by a complete loss of transmission. In 2025, we therefore moved BC and CII to the Iridium Short Burst Data (SBD) service, as used by other remote networks (e.g., on the Greenland Ice Sheet: Fausto et al., 2021). The SC station was not converted to Iridium SBD in 2024 due to logistical, financial, and time constraints and therefore limited data are only currently available via data via direct download. The PH station was switched to the Nepal Telecom 4G network in 2025. Though only limited variables are transmitted through SBD, the new data transmitted from SBD and BGAN-INMARSAT are not included in the current Zenodo archive (Khadka, 2026). Additional data will be added to the repository following retrieval, quality control, and validation.

184 Table 1. Locations of AWSs, data availability, sensors and their height from the surface during the installation (updated from
185 Matthews et al. (2020a)).

	Phortse (PH)	Base Camp (BC)	Camp II (CII)	South Col (SC) 2019	South Col (SC) 2022	Balcony (BA)	Bishop Rock (BR)
Lat, Lon, and Elevation	27.8456°N 86.7472°E 3,810 m	27.9952°N 86.8406°E 5,315 m	27.9810°N 86.9023°E 6,464 m	27.9719°N 86.9295°E 7,945 m	27.9719°N 86.9295°E 7,945 m	27.9826°N 86.9292°E 8,430 m	27.98805°N 86.92521°E 8,810 m
Data availability	April 2019 to April 2025	October 2019 to April 2025	May 2019 to April 2025	June 2019 to July 2021	May 2022 to April 2025	May 2019 to January 2020	May 2022 to July 2023
Sensor level above ground (m)	2 m for temperature and humidity, 2.3 m for wind	2 m	2 m	1.5 m for temperature and humidity, 2m for wind	1.5 m for temperature and humidity, 2m for wind	1.5 m for temperature and humidity, 2 m for wind	1.5 m for temperature and humidity, 2 m for wind
Air temperature sensor	Vaisala HMP155A-L5-PT; CS109	Vaisala HMP155A-L5-PT; CS109	Vaisala HMP155A-L5-PT; CS109	Vaisala HMP155A-L5-PT; CS109	2 × Vaisala HMP155A-L5-PT	Vaisala HMP155A-L5-PT; CS109	2 × Vaisala HMP155A-L5
Relative humidity sensor	Vaisala HMP155A-L5-PT	Vaisala HMP155A-L5-PT	Vaisala HMP155A-L5-PT	Vaisala HMP155A-L5-PT	2 × Vaisala HMP155A-L5-PT	Vaisala HMP155A-L5-PT	2 × Vaisala HMP155A-L5-PT
Wind speed and direction sensor	R.M. Young 05108-45	R.M. Young 05108-45	R.M. Young 05108-45	2 × R.M. Young 05108-45	Polycarbonate R.M. Young 05108-45, Richards C5C anemometer, Pitot tube	2 × R.M. Young 05108-45	Polycarbonate R.M. Young 05108-45, Richards C5C anemometer, Pitot tube
Air pressure sensor	Vaisala PTB 110	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210
Radiation sensor	2 × Hukseflux SR30 (up/down shortwave radiation); 2 × Hukseflux IR20 (up/down thermal radiation)	Hukseflux NR01	Apogee SN-500-SS	Hukseflux NR01	Hukseflux NR01	Hukseflux NR01	Hukseflux NR01
Precipitation sensor	OTT Pluvio ² and double-Alter shield	OTT Pluvio ² and double-Alter shield	-	-	-	-	-
Time lapse photo	-	Campbell Scientific Canada CCFC Field Camera	-	-	-	-	-
Present weather sensor	OTT Parsivel ²	OTT Parsivel ²	-	-	-	-	-
Relative surface elevation change sensor	Campbell Scientific SR50A	Campbell Scientific SR50A	Campbell Scientific SR50A	-	-	-	-
Datalogger	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X
Logger enclosure	Standard Campbell Scientific	Standard Campbell Scientific	Standard Campbell Scientific	Pelican case with military-spec quick-connects	Pelican case with military-spec quick-connects	Pelican case with military-spec quick-connects	Pelican case with military-spec quick-connects
Batteries	24 Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah

Charging	2 × 20 W solar panels	2 × 20 W solar panels	2 × 20 W solar panels	2 × 10 W solar panels	3 × 10 W solar panels	2 × 10 W solar panels	3 × 10 W solar panels
Telemetry	Inmarsat, Sierra wireless with NTC SIM	Thuraya; 400 MHz radio, Iridium	Thuraya; 400 MHz radio, Iridium	Thuraya; 400 MHz radio	Thuraya; 400 MHz radio	Thuraya; 400 MHz radio	Thuraya; 400 MHz radio
Sampling interval	3 s (wind); 60 s (radiation, air pressure, temperature, relative humidity, precipitation) 3600 s (present weather, relative surface elevation change)	5 s (wind); 60 s (temperature, relative humidity, precipitation); 600 s (air pressure); 3600 s (present weather)	60 s (temperature, relative humidity, wind); 600 s (radiation); 3600 s (relative surface elevation change)	5 s (wind); 60 s (temperature, relative humidity, radiation); 600 s (pressure)	5 s (wind); 60 s (temperature, relative humidity); 600 s (pressure)	5 s (wind); 60 s (temperature, relative humidity); 600 s (pressure)	5 s (wind); 60 s (temperature, relative humidity); 600 s (pressure)
Tripod	Campbell Scientific CM106B	Campbell Scientific CM106B	Campbell Scientific CM106B	Custom Aluminum	Custom Aluminum	Custom Aluminum	Custom Aluminum
Approximate Weight	-	-	-	Total: 50 kg Pelican case with logger: 8 kg Pelican case with batteries: 16 kg Tripod: 7 kg Crossarms, mounts, and bolts: 11 kg Sensors: 8 kg	Total: 52 kg Pelican case with logger: 8 kg Pelican case with batteries: 16 kg Tripod: 7 kg Crossarms, mounts, and bolts: 11 kg Sensors: 10 kg	Total: 50 kg Pelican case with logger: 8 kg Pelican case with batteries: 16 kg Tripod: 7 kg Crossarms, mounts, and bolts: 11 kg Sensors: 8 kg	Total: 52 kg Pelican case with logger: 8 kg Pelican case with batteries: 16 kg Tripod: 7 kg Crossarms, mounts, and bolts: 11 kg Sensors: 10 kg

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187 3. Data treatment and quality control procedure

188 Data gaps, sensor failures, and erroneous readings were common due to factors such as riming (icing of
189 sensors), heavy snowfall partially or completely burying the upper stations, battery depletion, extreme
190 temperature fluctuations, and communication failures. Acknowledging these challenges, we implemented,
191 a multistage quality control (QC) procedure to identify and flag spurious data points (Figure 2).

192 Our QC protocol takes a tiered approach, progressing from simple flagging to more complex, variable-
193 specific corrections. The procedures applied to the raw dataset are as follows:

- 194 • **Data flagging:** Where available, manufacturer-provided diagnostic data (Table S1) and internal
195 sensor flags were used to identify and filter out physically implausible or erroneous observations.
- 196 • **Relative humidity correction:** Physically, RH cannot exceed 100% under stable conditions. Any
197 instances in which RH was greater than 100% were assumed to be caused by sensor uncertainty or
198 rapid cooling events, and were capped at 100%. Artificially low values were also present in the raw
199 measurements due to the logger program calculating RH with respect to water rather than ice when
200 air temperatures were below 0 °C. We therefore corrected these instances by computing vapour
201 pressure (e) from measured RH, and saturation vapour pressure (e_s) with respect to ice using the air
202 temperature (Buck, 1981, 1996). Corrected RH was hence $100 \times (e/e_s)$.

- **Wind sensor freezing detection:** Periods of zero wind speed coupled with zero wind direction variability are a strong indicator of sensor freezing (e.g., encased in rime ice). These data points were identified and removed from the dataset rather than being treated as valid calm conditions.
- **Shortwave radiation corrections:**
 - **Night time values:** All incoming shortwave radiation below 7 W m^{-2} (a common threshold for sensor uncertainty during night time) were set to zero (Shea et al., 2015; Khadka et al., 2022).
 - **Albedo-based correction:** Fresh snowfall or deposition can accumulate on the upward-facing pyranometer, temporarily capping or shading the sensor. This obstruction leads to a substantial underestimation of incoming shortwave radiation (SW_{in}), while the downward-facing sensor continues to accurately measure the outgoing shortwave radiation (SW_{out}) of the fresh snow surface. Consequently, the calculated surface albedo ($\alpha = \text{SW}_{\text{out}}/\text{SW}_{\text{in}}$) can artifactually exceed realistic threshold values for snow (typically $\alpha > 0.95$). To address this instrumental artifact and ensure strict quality control, we adopted the correction protocol developed by Shea et al. (2015) to adjust the compromised SW_{in} values during these specific cases. Specifically, for periods where the calculated albedo exceeded 0.95, it was assumed that SW_{in} was underestimated (e.g., due to sensor riming or a tilted sensor). SW_{in} was recalculated as $\text{SW}_{\text{out}}/0.95$ to provide a more realistic estimate (Shea et al., 2015; Khadka et al., 2022).
- **Precipitation:** The Pluvio² weighing precipitation gauges were equipped with double-Alter shields to minimize wind-induced undercatch (Figure S1). Only positive accumulation records were considered. No correction for wind undercatch was applied in this dataset; users are advised to apply such corrections using established methods (e.g., Kochendorfer et al., 2022; Graves et al., 2026).

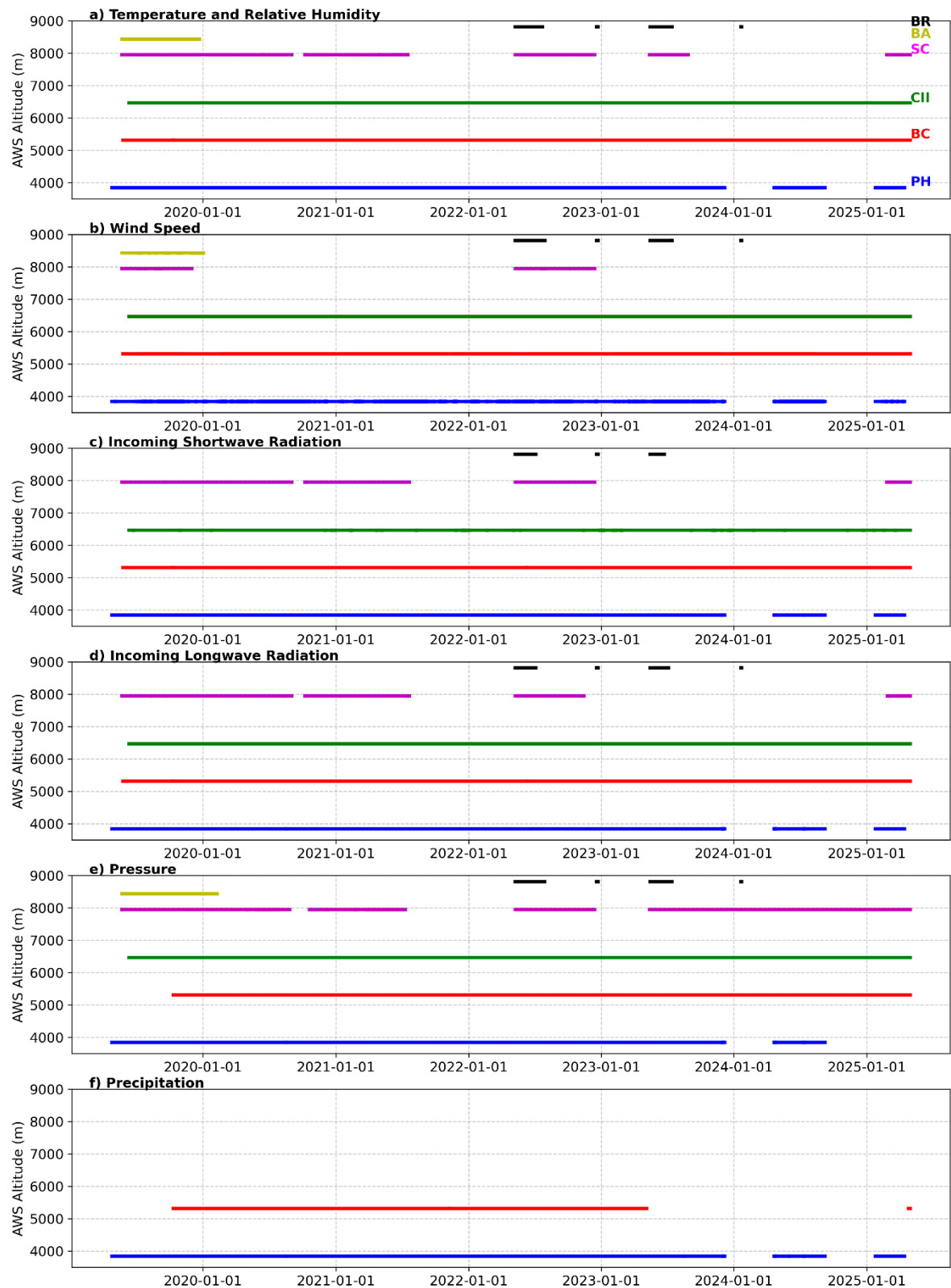


Figure 2. Periods of data availability for the principal sensors at each AWS from installation until May 2025. Solid horizontal lines indicate periods for which quality-controlled observations are available.

4. Climatology of the region

Figure 3 presents the annual cycles of precipitation and temperature at PH and BC for December 2019–November 2022, together with monthly mean, minimum, and maximum temperatures based on all available observations at CII, SC, BA, and BR. Whilst this is a very short period for understanding climate variability, there is a clear seasonal pattern in precipitation and temperature at both sites. Across the network, the lowest temperatures generally occur during winter (December–February). Temperatures then rise progressively during the pre-monsoon season (March–May), coinciding with increasing incoming shortwave radiation and longer daylight duration (Figure S4). The mean annual temperature was 4.1 °C at PH, -3.1 °C at BC, and -10.2 °C at CII. The mean monthly temperature amplitude was 6.7 °C (max 8.0 °C in March, min 4.6 °C in July) at PH, 6.5 °C (max 7.9 °C in March, min 4.9 °C in December) at BC and 6.4 °C (max 7.8 °C in March, min 3.6 °C in December) at CII, respectively. At SC, July was the warmest month, with a mean temperature of -12.2 °C and a mean diurnal range of 10.2 °C. February was the coldest month, with a mean temperature of -29.7 °C and a mean diurnal range of 4.4 °C. Precipitation at PH and BC also clearly delineates the seasonal cycle: winter is predominantly dry, precipitation gradually increases during the pre-monsoon, and the largest amounts occur during the June–September monsoon season, which accounts for 72% and 77% of the annual precipitation at PH and BC, respectively. Precipitation subsequently declines during the post-monsoon period as cooler and drier winter conditions become established.

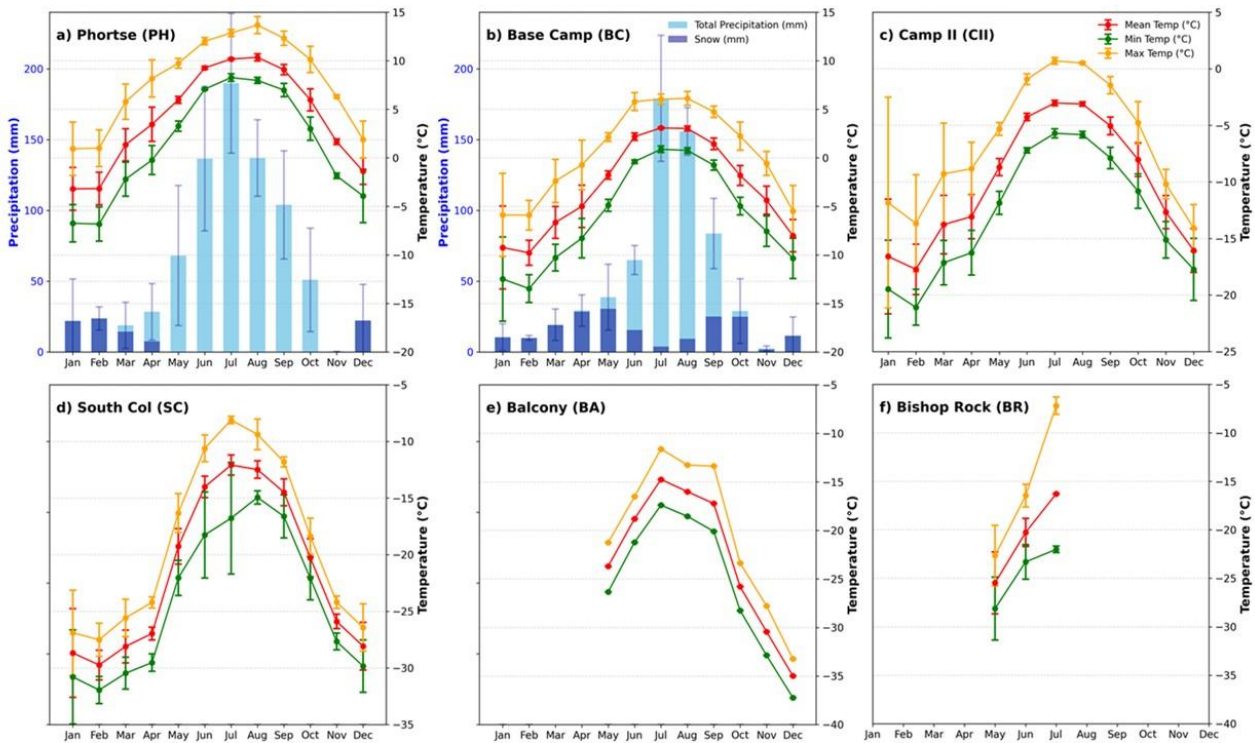


Figure 3. Mean annual cycle of monthly precipitation (snow and total precipitation in mm liquid water equivalent, histograms) and monthly mean, minimum and maximum air temperature (T , lines) during December 2019–November 2022 at PH, BC, and CII AWSs (a-c) and monthly mean, minimum and maximum temperature for all the available period for SC, BA and BR AWSs (d-f). The error bars represent the monthly standard deviation for all different variables and BA error bars are omitted because of the limited number of observations.

Seasonal mean values, and elevation gradients between the PH and BC AWSs (separated by ~1,500 m) also reveal some interesting characteristics (Table 2). While these linear elevation gradients provide a useful

baseline, it is important to note that the precipitation gradient across this elevational range is fundamentally non-linear, with the rate of change varying significantly between specific altitudes and locations. When calculated as a single linear gradient across this elevational range, the mean annual precipitation gradient was -107 mm km^{-1} , but it declines by almost 50 % during the monsoon to -56 mm km^{-1} . This contrast indicates that while the monsoon brings the highest total volume of water, non-monsoonal seasons (winter, pre-, and post-monsoon) feature much more dramatic relative precipitation drops with increasing elevation. Overall, the amount of precipitation measured at both observing sites (PH and BC) were higher than those reported at Pheriche (4,200 m asl; 540 mm during November 2016–December 2020) and Pyramid (5,050 m asl; 449 mm during 1994–2012 and 591 mm during November 2016–December 2020) (Khadka et al., 2022; Salerno et al., 2015). Similarly, between PH and BC, the mean temperature gradient (TG) is $-4.8 \text{ }^{\circ}\text{C km}^{-1}$ with least negative in winter ($-4.5 \text{ }^{\circ}\text{C km}^{-1}$) and most negative during the pre-monsoon season ($-5.4 \text{ }^{\circ}\text{C km}^{-1}$). When data from four stations with minimal data gaps (PH, BC, CII, and SC) are used to calculate linear and non-linear TGs, the resulting gradients are more strongly negative than those calculated using only the PH and BC AWSs. Both the seasonal and annual TGs derived from all four stations (Table 2) are more negative (pre-monsoon, monsoon, annual: -6.5 , -5.7 , and $-6.0 \text{ }^{\circ}\text{C km}^{-1}$, respectively) than the values previously reported by Salerno et al. (2015) and Graves et al. (2026), calculated using several stations in the Koshi basin between 1,000–8,000 m asl and Dudh Koshi basin between 2,600–8,400 m asl. However, the TG calculated from all four AWSs (Table 2) is comparable at both seasonal and annual scales to the TG reported by Salerno et al. (2015). Crucially, we note that reported non-linearity in the temperature-altitude relationship in the Khumbu region (Khadka et al., 2021) limits the comparability of lapse rates calculated across different elevational ranges. Consequently, we follow Graves et al. (2026) and provide a non-linear equation for the temperature gradients between PH and SC (Table 2; Figure S3).

Both incoming longwave (LWin) and shortwave radiation (SWin) exhibit strong seasonality and clear variation with altitude (Figure S4). Both LWin and SWin reach their lowest values during winter when temperatures are coldest. As the pre-monsoon begins, rising air temperatures drive a steady increase in LWin, which remains high throughout the monsoon season. Notably, the maximum daily LWin at PH during the monsoon exceeds 350 W m^{-2} , while at SC it remains below $\sim 250 \text{ W m}^{-2}$. This contrast likely reflects both the lower atmospheric temperature at SC and differences in effective atmospheric emissivity, potentially associated with lower water-vapour content and reduced cloud cover at higher elevations.

SWin is lowest during mid-winter and gradually increases toward the pre-monsoon period. However, the influence of monsoonal cloud cover is weaker at higher-elevation sites (CII and SC) compared to lower-elevation stations (PH and BC), indicating reduced atmospheric moisture at higher altitudes and supporting the presence of a strong negative precipitation gradient with elevation (Graves et al., 2026).

Table 2. Mean seasonal and annual temperature ($^{\circ}\text{C}$) and precipitation (P , mm) at PH and BC AWSs and the calculated linear Temperature and Precipitation gradients (TG and PG respectively), and the non-linear TG equation derived across the stations. *z represents the altitude in kilometres (km) used to calculate the non-linear TG.

Season	Base Camp (BC)		Phortse (PH)		TG	TG	TG	PG
	Temperature ($^{\circ}\text{C}$)	Precipitation (mm)	Temperature ($^{\circ}\text{C}$)	Precipitation (mm)	from PH and BC AWSs ($^{\circ}\text{C km}^{-1}$)	from PH, BC, CII and SC AWSs ($^{\circ}\text{C km}^{-1}$)	non-linear equation from PH, BC, CII and SC AWSs ($^{\circ}\text{C km}^{-1}$) ¹⁾	from PH and BC AWSs (mm km^{-1})

Winter (Dec-Feb)	-8.8	27	-2.1	56	-4.5	-6.5	-0.75z ² + 2.4z - 0.7	-20/-73
Pre-Monsoon (Mar-May)	-4.5	87	3.6	115	-5.4	-6.7	-0.5z ² - 0.75z + 13.8	-19/-22
Monsoon (Jun-Sept)	2.4	484	9.7	567	-4.8	-5.6	-0.26z ² - 2.53z + 23.2	-56/-12
Post-Monsoon (Oct-Nov)	-3.1	31	3.9	51	-4.6	-6.6	-0.78z ² + 2.56z + 5.4	-13/-44
Annual	-3.1	629	4.1	790	-4.8	-6.3	-0.57z ² + 0.42z + 10.4	-107/-17

5. Comparison with ERA5

Monitoring the meteorology at the highest altitudes in the Himalaya at elevations where glaciers are accumulating mass, and where mountaineers are most at risk from extreme weather provides the greatest test to observational efforts. Accordingly, there is considerable interest in using reanalysis data to extend brief in-situ records. However, to facilitate such extensions, it is necessary to establish the extent to which such reanalysis products can reproduce the observed meteorology (Khadka et al., 2022). ERA5, the fifth-generation global reanalysis produced by ECMWF, provides hourly atmospheric variables from 1940 onward at multiple pressure levels and at relatively high spatial resolution and is widely used as a reference dataset (Hersbach et al., 2020). While adjacent higher AWSs (BR and BA) suffer from highly limited data availability, SC AWS has longer observational record and remains operational. This is also the location of the highest-altitude camp on the main southern (Nepalese) Everest climbing route, where critical resources (e.g., tents and oxygen) are stored, and where climbers can spend considerable time. Consequently, we focus on comparisons between temperature, relative humidity and wind speed between the SC AWS and ERA5 reanalysis (Hersbach et al., 2020) data extracted from the nearest grid point at the 350 hPa pressure level (most representative of the SC: mean air pressure 2019-2021 = 377 hPa). Our comparison is limited to air temperature—relevant for cold stress and with relatively high data completeness at the BA and BR sites.

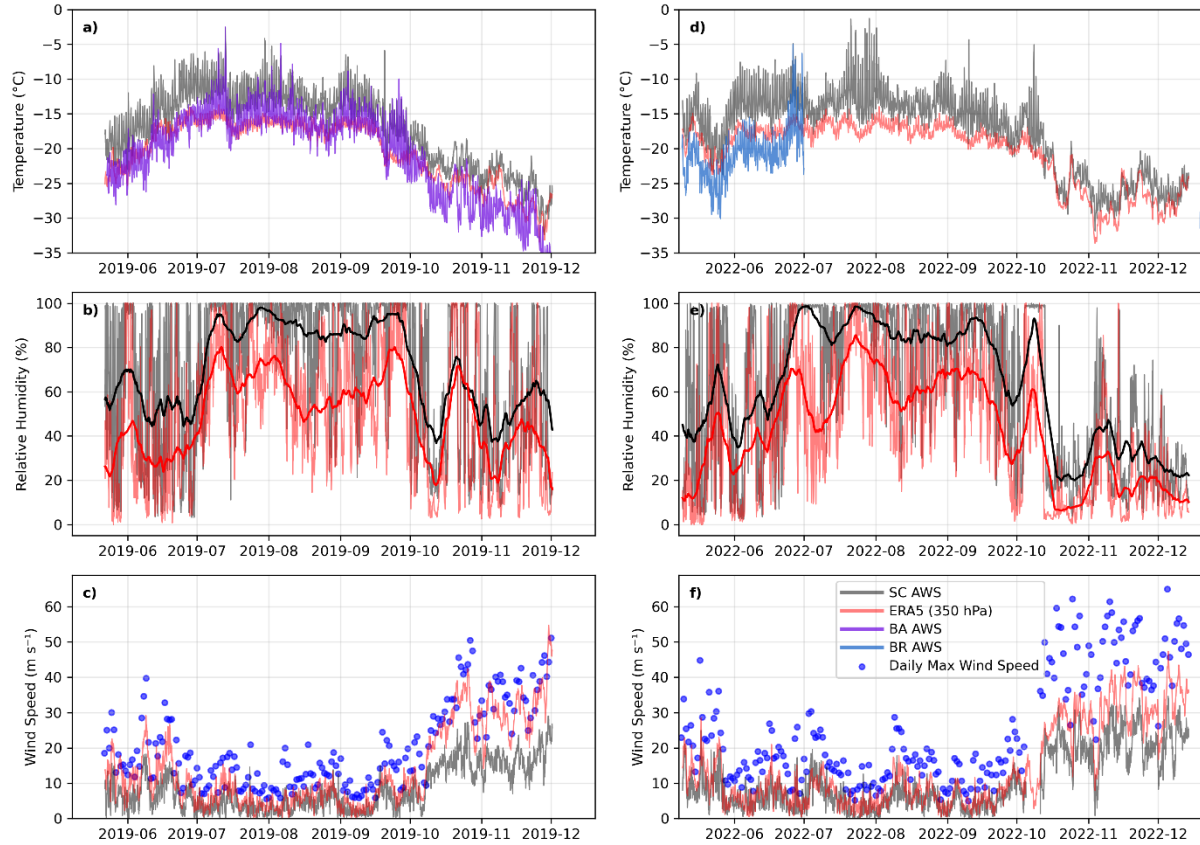


Figure 4. Hourly air temperature, relative humidity (with respect to water) and wind speed from the SC AWS and ERA5 350 hPa pressure level data (from the nearest grid point to the SC AWS) for the available data period of 2019 (a,b,c) and 2022 (d,e,f). The solid black and red lines represent the 10-day running means of relative humidity and the blue dots represent the observed daily maximum wind speed.

During both 2019 and 2022, air temperature exhibited reasonably close co-variation between the SC observations and ERA5, with an $R^2 > 0.6$ (Figure 4 and Table 3). ERA5 systematically underestimates air temperature relative to the observations, although some of that reflects the higher altitude (lower air pressure) at 350 hPa relative to the SC data. Diurnal variability is also considerably greater in the SC dataset (Figures S5 and S6), likely reflecting the influences of surface heat fluxes at SC, which are missing in ERA5 as this (higher altitude) pressure level is representative of the free atmosphere. To further assess the representativeness of ERA5 at high elevations, we compared ERA5 350 hPa temperatures with shorter observational records from BA (mean air pressure = 354 hPa) and BR (mean air pressure = 340.5 hPa). In 2019, the coefficient of determination (R^2) between ERA5 and BA found 0.85, while in 2022 the R^2 between ERA5 and BR was 0.56. Despite the shorter datasets, these results indicate that ERA5 temperatures at 350 hPa track observed variability in atmospheric conditions at these very high elevation sites.

The R^2 values for AWS and ERA5 relative humidity were 0.49 and 0.57 in 2019 and 2022; however, the MAE and RMSE for the relative humidity are $>20\%$. The 10-day running means of relative humidity from both the AWS observations and ERA5 clearly capture the seasonal transitions, with monsoon onset at SC occurring on 1 July 2019 and 14 June 2022 (Figure 4).

In both years, wind speed exhibited the highest correlation between SC observations and ERA5 ($R^2 = 0.70$). ERA5 consistently overestimated mean wind speeds at SC, with MAE values of 4.8 and 5.3 m s^{-1} in 2019 and 2022, respectively (Table 3 and Figure 4). This is again consistent with the ERA5 grid point being representative of the higher-altitude free atmosphere; frictional drag at the SC reduces the wind speed. We

also observe faster winds in the post-monsoon in 2022 compared to 2019. Based on the generally good agreement between ERA5 reanalysis data and observations at the SC, we anticipate that the reanalysis could be used to gap-fill and extend intermittent meteorological records from Mount Everest’s upper slopes—correcting the time-varying biases using empirical-statistical, or machine-learning based approaches (Van Wyk de Vries et al., 2024; Potocki et al., 2022).

Table 3. Values of statistical metrics (R^2 , MAE, RMSE) comparing hourly SC AWS observations with ERA5 350 hPa temperature (T), relative humidity (RH) and wind speed (WS) for 2019 and 2022.

Year	Variables	R^2	MAE	RMSE
2019	T (°C)	0.67	3.7	4.1
	RH (%)	0.49	24.6	31.4
	WS (m s ⁻¹)	0.70	4.8	5.6
2022	T (°C)	0.62	3.1	3.6
	RH (%)	0.57	23.4	30.4
	WS (m s ⁻¹)	0.70	5.3	6.1

6. Research insight and importance of the data

Observations from the SC (Figure 4) highlight the potential for mean winds exceeding 30 m s⁻¹ and gusts above 60 m s⁻¹ that can be extremely dangerous for mountaineers by increasing the risk of being blown over and the probability of cold injury (Sherpa et al., 2023; Van Wyk de Vries et al., 2024). Elsewhere, atmospheric pressure data from the AWS network described here have shown that oxygen availability at the summit is highly variable on synoptic timescales, as it depends on the partial pressure of atmosphere. Consequently, the “apparent elevation” of Mt. Everest (i.e., how high the mountain would feel without supplemental oxygen) can vary by almost 750 m, and during the most challenging winter conditions an ascent without supplemental oxygen may be impossible (Matthews et al., 2020b). Accurately forecasting wind speeds and oxygen variability for the upper slopes of Mount Everest is therefore of high importance for increasing safety on the mountain. The data from the AWSs presented here provide the foundation to achieve such improvements. At a minimum, they can be used to assess uncertainty in the freely available forecasts widely used by expeditions (Matthews et al., 2020b); but they can also be used to train model output statistics including novel applications of machine learning to provide improved, hyper-local forecasts for identifying optimal climbing windows (Van Wyk de Vries et al., 2024).

The AWS data shared here can also be extremely useful for understanding cryosphere-climate interactions at the highest elevations within HMA. For instance, the archive has already been used to estimate the surface energy balances at the summit of Mt. Everest (Matthews et al., 2020a), and for the South Col Glacier (at ~8,000 m asl), revealing a high-altitude system that might be acutely sensitive to changes in effective precipitation due to extremely high levels of insolation and thus highly responsive to albedo variations (Matthews et al., 2020a; Potocki et al., 2022; Brun et al., 2023). However, significant uncertainties still remain, mainly because the observational record is short. These could be improved by extending the analysis with downscaled reanalysis products like ERA5.

The data here are useful not only for assessing cryosphere-climate interactions at extreme elevations but could be used to improve understanding of surface energy and mass balances within the ablation areas of the region’s glaciers, and at lower elevations. The precipitation measurements, for instance, are particularly high quality, as they were collected behind double-Alter shields to reduce undercatch (which likely accounts for the greater accumulations relative to nearby stations without such shields: Pheriche and Pyramid), and hence offer a valuable opportunity to constrain mass inputs. More generally, when used in combination with the generally lower-altitude observations from the GLACIOCLIM and EvK2CNR networks, the data shared here can improve quantification of elevational gradients in key meteorological variables needed in

distributed (e.g., glacier or hydrological) modelling assessments across up to approximately five vertical kilometres, and hence the entire glacierised elevational range of the Khumbu region.

Data across such a large elevational range could also provide valuable insight into regional-scale atmospheric dynamics. For instance, the timing and character of the monsoon's arrival—critical for determining the annual precipitation totals (Perry et al., 2020), and a key control on melt energy (Khadka et al., 2021; Matthews et al., 2020a) can be assessed right up to the upper accumulation area of the Khumbu Glacier. Important further work might improve understanding of the relevant physical drivers behind elevational differences in the monsoon's arrival, how they interact with local anabatic and potential katabatic forcing, and how they might change with further global warming (Salerno et al., 2023).

Ultimately, though, these data might be used in ways far beyond the illustrations above. The upper slopes of Mount Everest represented the last frontier for human exploration, reached successfully by humans 42 years after the South Pole was attained. Meteorological measurements from the highest reaches only began in 2022 (at the BR). We are still, therefore, at the very beginnings of exploring the weather of this extreme environment, and the list of questions that these data might help answer from disciplines beyond the climate sciences (e.g., biology: Dragone et al., 2023) might conceivably grow rapidly.

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Authors contributions

BP, TM, and AE planned the initial data collection strategy. BP and TM managed the funding and collaboration with the National Geographic Society and Rolex for the 2019-2025 period. AK, BP, TM, and TGS installed and maintained the AWSs with the Sherpa supports. BP and TM worked closely with Campbell Scientific to design and program the AWSs. AK, BP, and TM contributed to the data analysis, manuscript designing. AK prepared the paper with contributions from all the co-authors.

Data availability

The quality controlled dataset is available in CSV format from Zenodo (<https://doi.org/10.5281/zenodo.18849098>; Khadka, 2026). Selected data can also be downloaded from the National Geographic Society weather-data portal (<https://www.nationalgeographic.org/projects/perpetual-planet/everest/weather-data/>). The raw disdrometer and all available wind speed data are available at Zenodo. Additionally, the data processing code is available at https://github.com/arbindrakhadka/AWS_QC.

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