



1 **Weather station data from the Mount Everest region, Nepal: 3,810-**  
2 **8,810 m above sea level**

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21

## 22 **Abstract**

23 The National Geographic Rolex Perpetual Planet Everest expeditions 2019-2022 installed a network of  
24 Automatic Weather Stations (AWSs) to improve understanding of the climate at high altitudes in the Nepal  
25 Himalaya. This knowledge is critical in the Mount Everest (Khumbu) region, due to its extreme altitude,  
26 popularity amongst trekkers and mountaineers, and its importance as a source of freshwater for downstream  
27 communities. Here we present quality controlled (QC) meteorological data from six AWSs from Phortse  
28 (3,810 m above sea level, m asl) to Bishop Rock (8,810 m asl) in the Everest region, including the seasonal  
29 climatology, and a comparison with ERA5 reanalysis data from the South Col AWS. The data is accessible  
30 from <https://doi.org/10.5281/zenodo.18849098> (Khadka, 2026).

## 31 **1. Introduction**

32 Field research in High Mountain Asia (HMA) which has the most glacier area outside of the polar regions  
33 (Brun et al., 2017; Pfeffer et al., 2014) is extremely difficult. The region's high altitude results in low  
34 barometric pressure (and hence relatively low oxygen availability: Matthews et al., 2020a), and extreme  
35 weather, challenging personnel and equipment alike in the task of assembling high-quality, long-term  
36 observational datasets (Salerno et al., 2015; Shea et al., 2015; Khadka et al., 2022; Matthews et al., 2020a).  
37 However, there are strong incentives to overcome these difficulties. First, the region is an important  
38 freshwater source for a vast number of communities downstream (Immerzeel et al., 2010). Second, the  
39 extreme weather, combined with steep terrain, places the region at a relatively high risk of  
40 hydrometeorological hazards (Miner et al., 2020). Establishing meteorological observational networks both  
41 helps to improve understanding of water resource availability in a changing climate, and to reduce  
42 hydrometeorological risks.

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

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

61 Despite significant investments by numerous research groups, critical gaps persist in understanding HMA  
62 cryospheric processes, climate change signals, and data dependability. Weather forecasts for peaks above  
63 6,000 m asl—of life-and-death relevance for the region's many mountaineers (Matthews et al., 2020a), also  
64 remain highly uncertain due to the lack of ground-validated observations. Furthermore, a scarcity of high-



65 quality, elevation-dependent datasets hinders efforts to refine regional climate models and downscale  
66 reanalysis products, which is necessary to understand longer-term, larger scale climate change in this region  
67 (Khadka et al., 2022).

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

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

## 82 2. Observation area and Data

83 The geographical locations of the different AWSs are shown in Figure 1. The five stations were initially  
84 installed in the primary Khumbu valley from Phortse (3,810 m asl; hereafter referred as PH), Base Camp  
85 (5,315 m asl; hereafter referred as BC) Camp II (6,464 m asl; hereafter referred as CII) South Col (7,945 m  
86 asl; hereafter referred as SC) and Balcony (8,430 m asl; hereafter referred as BA) during the 2019 expedition  
87 (Matthews et al., 2020a). The BA station was toppled by extreme winds and anchor failure in January 2020,  
88 so in May 2022 a team of researchers and Sherpa returned to install a new AWS at Bishop Rock (8,810 m  
89 asl; hereafter referred as BR), remove the BA station, and upgrade the station at the SC (Matthews et al.,  
90 2022).

91 Data have been recorded using Campbell scientific CR1000X dataloggers, at intervals ranging from 10  
92 minutes to daily. However, here we present quality-controlled hourly data sets in **University Coordinated**  
93 **Time (UTC)**. The respective variables and sensors include air temperature (T), relative humidity (RH), wind  
94 speed (WS), radiation variables (Incoming (in) and outgoing (out) shortwave (SW) and long wave (LW)  
95 radiation), pressure (Pa), and precipitation (P) (Table 1). We also include data from experimental pitot wind  
96 sensors installed at the SC and BR in 2022.



97

98 *Figure 1. Geographical location of different automatic weather stations in the Khumbu region of Nepal. The plus symbol represents*  
99 *camp in the valley including Everest Base Camp and the Changri Nup point is the area where Meteorological glaciological*  
100 *observation has been monitored since 2010 and the red lines represents the normal climbing route to Mount Everest from South*  
101 *side.*

## 102 2.1 AWS details and measured variables

103 Two types of tripods were used for the AWSs: the Campbell Scientific CM106B, which has an adjustable  
104 height of between 2.1 and 3 m, was used for the lower three (PH, BC and CII) AWSs. The tripod was affixed  
105 with a datalogger box, solar panel, various sensors and an antenna for grounding to protect against lightning  
106 (Table 1, see Supplementary Information for photographs). An OTT HydroMet Pluvio<sup>2</sup> with a double alter  
107 shield was installed separately at the PH and BC AWSs to measure precipitation. For the upper three (SC,  
108 BA and BR) AWSs, a 7-kg custom aluminium tripod designed by Campbell Scientific specifically for  
109 Everest was used (Matthews et al., 2020a). The PH and BC AWSs were secured in the soil with stakes  
110 pushed 0.5–1 m into the ground, while the other higher AWSs were bolted on to rocks and also guyed to  
111 additional anchor points. For the lower AWSs, the batteries were installed inside the data logger box and on  
112 a tripod. For the upper AWSs, the batteries were installed in a separate insulated box to protect it from very  
113 low temperatures, and both data logger and battery boxes were separately bolted to the rock to reduce wind  
114 drag on the tripod. The overall weight of the lower AWSs is approximately 60 kg and the upper AWSs  
115 weigh 52 kg, including the additional pitot tube (~2 kg) and other sensors added in 2022 (Matthews et al.,  
116 2020a, 2022). The BA AWS was found to have been toppled during the 2020 maintenance visit, possibly  
117 due to extreme wind gusts; however, the other tripods remain in position at the time of writing. Below, we



118 detail measurement details for the respective meteorological variables. This information is also summarised  
119 in Table 1.

### 120 **2.1.1 Air Temperature and Relative Humidity**

121 Air temperature (°C) and relative humidity (%) are measured using a Vaisala HMP155A-L5-PT sensor  
122 installed in a naturally ventilated METSPEC 14-plate solar radiation shield. Additionally, a CS109  
123 temperature probe, ventilated by a METSPEC 6-plate solar radiation shield, was installed for air temperature  
124 measurement at each station in 2019. While both shield types reduce radiative heating, the absence of active  
125 aspiration, particularly for the less protected CS109 with its 6-plate shield may introduce a positive diurnal  
126 temperature bias. In 2022, however, only dual Vaisala HMP 155A-L5-PT sensors with METSPEC 14-plate  
127 solar radiation shields were installed in the SC and BR AWSs. **The sensors are installed 2 m from the ground**  
128 **for the PH, BC and CII AWSs, and 1.5 m for the higher AWSs.**

### 129 **2.1.2 Wind Speed and Direction**

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

### 138 **2.1.3 Air Pressure**

139 The measurement of barometric air pressure (hPa) at PH is achieved using the Vaisala PTB 110, whilst the  
140 Vaisala PTB210 is employed in all other AWSs as higher AWSs weather is comparatively harsh with lower  
141 pressure. The sensors are installed within the data logger box of all AWSs. However, the data logger box of  
142 the three lower AWSs (PH, BR, and CII) is located on the tripod mast, at a distance of 1-1.5 m above the  
143 ground surface.

### 144 **2.1.4 Radiation**

145 The measurement of the four components of radiation is facilitated by the Hukseflux SR30 (up/down  
146 shortwave radiation); Hukseflux IR20 (up/down longwave radiation) at PH; Apogee SN-500-SS at CII; and  
147 Hukseflux NR01 at other AWSs using the cross arm (Figure S1, S2). The radiation sensors are mounted on  
148 crossarms at approximately 1.5 m above the surface at all locations.

### 149 **2.1.5 Precipitation**

150 At the PH and BC AWSs, the weighing OTT Pluvio<sup>2</sup> was installed with double alter shields, with a height  
151 of 1.5 m (from the surface at the mouth of Pluvio). At both sites the OTT Pluvio<sup>2</sup> is partially filled with an  
152 ecologically friendly antifreeze agent, which is replaced regularly when the reservoir is emptied during  
153 regular maintenance visits.

### 154 **2.1.6 Time Lapse Photo**

155 In addition to the the meteorological measurement at BC AWS, a Campbell Scientific CCFC Field  
156 Camera was installed looking eastward toward the summit of Mt Everest. **The camera captures**  
157 **photographs two times a day; at 0937 Nepal time (NPT) (0352 UTC) and at 1437 NPT (0852 UTC),**  
158 **respectively** (Grey et al., 2022).

## 159 **2.2 Real-time data transfer**

160 At the beginning (2019) all the stations (except PH) were configured to transmit real-time data using the  
161 Thuraya satellite network. After the failure of the Thuraya 3 satellite in April 2024, connectivity became



162 intermittent, and then stopped altogether. In 2025, we therefore moved BC and CII to the Iridium Short  
163 Burst Data (SBD), as used by other remote networks (e.g., on the Greenland Ice Sheet: Fausto et al., 2021).  
164 The SC station was not converted to Iridium SBD in 2024 due to logistical, financial, and time constraints  
165 and therefore limited data are only currently available via data via direct download. The PH station was  
166 originally configured to transfer data using the network but was switched to the Nepal Telecom 4G network  
167 in 2024. Though only limited variables are transmitted through SDB, the new data transmitted from SDB  
168 and BGAN-INMARSAT are not included in the <https://doi.org/10.5281/zenodo.18849098> (Khadka, 2026).  
169 The new data will be added after the next fieldwork probably in spring 2026.



170 Table 1. AWSs location, data availability, sensors and their height from the surface during the installation (updated from  
 171 Mattmendhews et al. 2020a).

	Phortse (PH)	Base Camp (BC)	Camp (CIII)	South Col (SC) 2019	South Col (SC) 2022	Balcony (BA)	Bishop Rock (BR)
<b>Lat, Lon, and Elevation</b>	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
<b>Data availability</b>	April 2019 to present	October 2019 to-present	May 2019 to present	June 2019 to July 2021	May 2022 to present	May 2019 to January 2020	May 2022 to July 2023
<b>Sensor level above ground (m)</b>	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
<b>Air temperature sensor</b>	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
<b>Relative humidity sensor</b>	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
<b>Wind speed and direction sensor</b>	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
<b>Air Pressure sensor</b>	Vaisala PTB 110	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210	Vaisala PTB210
<b>Radiation sensor</b>	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
<b>Precipitation sensor</b>	OTT Pluvio <sup>2</sup> and double alter shield	OTT Pluvio <sup>2</sup> and double alter shield	-	-	-	-	-
<b>Time Lapse Photo</b>	-	Campbell Scientific Canada CCFC Field Camera	-	-	-	-	-
<b>Present weather sensor</b>	OTT Parsivel <sup>2</sup>	OTT Parsivel <sup>2</sup>	-	-	-	-	-
<b>Relative surface elevation change sensor</b>	Campbell Scientific SR50A	Campbell Scientific SR50A	Campbell Scientific SR50A	-	-	-	-
<b>Data Logger</b>	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X	Campbell Scientific CR1000X
<b>Logger enclosure</b>	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
<b>Batteries</b>	24 Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah	3 × 8Ah



Charging	2 × 20W solar panels	2 × 20W solar panels	2 × 20W solar panels	2 × 10W solar panels	3 × 10W solar panels	2 × 10W solar panels	3 × 10W 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	Not available	Not available	Not available	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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### 173 3. Data treatment and quality control procedure

174 Data gaps, sensor failures, and erroneous readings were common due to factors such as riming (icing of  
 175 sensors), heavy snowfall partially or completely burying the upper stations, battery depletion, extreme  
 176 temperature fluctuations, and communication failures. Acknowledging these challenges, we implemented,  
 177 a multi-stage quality control (QC) procedure to identify and flag spurious data points.

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

180 **Data flagging:** Where available, manufacturer-provided diagnostic data (Table S 1) and internal sensor  
 181 flags were used to identify and filter out physically implausible or erroneous observations.

182 **Relative humidity correction:** Physically, RH cannot exceed 100% under stable conditions. Any instances  
 183 in which RH was greater than 100% were assumed to be caused by sensor uncertainty or rapid cooling  
 184 events, and were capped at 100%. Artificially low RH in our raw measurements were also present due to  
 185 the logger program calculating RH with respect to water rather than ice when air temperatures were below  
 186 0 °C. We therefore corrected these instances by computing vapour pressure ( $e$ ) from measured RH, and  
 187 saturation vapour pressure ( $e_s$ ) with respect to ice using the air temperature (Buck, 1981, 1996). Corrected  
 188 RH was hence  $e/e_s$ .



189 **Wind sensor freezing detection:** Periods of zero wind speed coupled with zero wind direction variability  
190 are a strong indicator of sensor freezing (e.g., encased in rime ice). These data points were identified and  
191 removed from the dataset rather than being treated as valid calm conditions.

192 **Shortwave radiation corrections:**

193 **Night time values:** All incoming shortwave radiation below  $7 \text{ W m}^{-2}$  (a common threshold for  
194 sensor uncertainty during night time) were set to zero (Shea et al., 2015; Khadka et al., 2022).

195 **Albedo-based correction:** Fresh snowfall can cause the surface albedo ( $\alpha = \text{SW}_{\text{out}} / \text{SW}_{\text{in}}$ ) to  
196 exceed a realistic value for snow (typically  $\alpha \leq 0.95$ ). For periods where calculated albedo exceeded  
197 0.95, it was assumed that  $\text{SW}_{\text{in}}$  was underestimated (e.g., due to sensor rime or a tilted sensor).  
198  $\text{SW}_{\text{in}}$  was recalculated as  $\text{SW}_{\text{out}} / 0.95$  to provide a more realistic estimate (Shea et al., 2015;  
199 Khadka et al., 2022)

200 **Precipitation:** The Pluvio<sup>2</sup> weighing precipitation gauges were equipped with double alter shields to  
201 minimize wind-induced under-catch (Figure S1). Only positive accumulation records were considered. No  
202 correction for wind under-catch was applied in this dataset; users are advised to apply such corrections using  
203 established methods (e.g., Kochendorfer et al., 2022).

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Figure 2. Time periods when stations/sensors were operational since the beginning of installation to the last field visit in May 2025. The solid lines represent the period of available data.

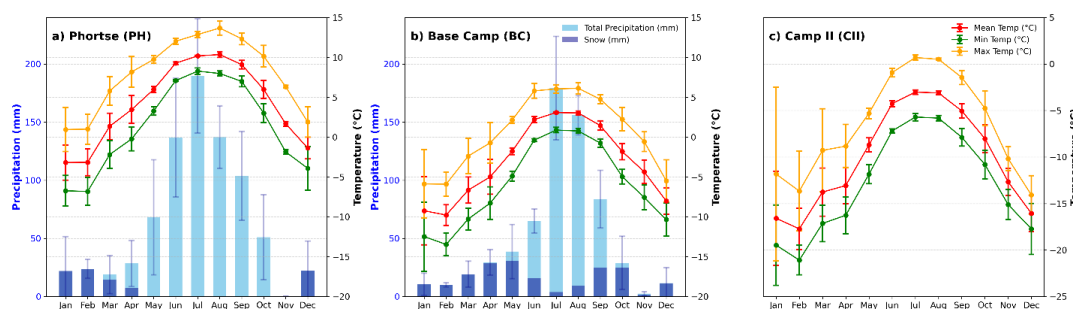


#### 208 4. Climatology of the region

209 Figure 3 shows the monthly precipitation and temperature (from December 2019 to November 2022; Figure  
 210 2) for PH (3,840 m) and BC (5,315 m), the two AWSs in the network that include measurements of  
 211 precipitation. Whilst this is a very short period for understanding climate variability, there is a clear seasonal  
 212 pattern in precipitation and temperature at both sites. The annual precipitation is 790 and 629 mm, with 72  
 213 and 77% of this falling during the monsoon at the PH and BC AWSs, respectively. The average annual  
 214 temperature at PH is 4.1 °C, BC is -3.1 °C and CII is -10.2 °C with monthly amplitude of temperature is 6.7  
 215 (max 8.0 °C in March, min 4.6 °C in July), 6.5 °C (max 7.9 °C in March, min 4.9 °C in December) and 6.4  
 216 (max 7.8 °C in March, min 3.6 °C in December), respectively.

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220 *Figure 3. Mean annual cycle of monthly precipitation (snow and total precipitation in mm liquid water equivalent, histograms) and*  
 221 *mean monthly mean, minimum and maximum air temperature (T, lines) during December 2019- November 2022 at PH, BC and CII*  
 222 *AWSs. The bar represents the standard deviation for all different variables. .*

223 Seasonal mean values, and elevation gradients between the Ph and BC AWSs (separated by ~1500 m) also  
 224 reveal some interesting characteristics (Table 2). The precipitation gradients average  $-107 \text{ mm km}^{-1}$  ( $-17 \%$   
 225  $\text{km}^{-1}$ ) average over three years, but it declines by almost 50 % during the monsoon (to  $-56 \text{ mm km}^{-1}/12 \%$   
 226  $\text{km}^{-1}$ ). Overall, the amount of precipitation measured at the both (PH and BC) observing sites is higher than  
 227 the amount measured at the Pheriche (4200 m asl: 540 mm) and Pyramid (5050 m asl: 449 and 591 mm) by  
 228 IRD stations (Khadka et al., 2022). Similarly, between the PH and BC, the mean temperature gradient is  $-$   
 229  $4.8 \text{ °C km}^{-1}$  with minimum  $-4.5 \text{ °C km}^{-1}$  during the winter and maximum  $-5.4 \text{ °C km}^{-1}$  during the Pre-  
 230 monsoon. Both seasonal and annual temperature gradients (Table 2) are also less negative than reported  
 231 previously (pre-monsoon, monsoon, annual:  $-6.5, -5.7, -6.0 \text{ °C km}^{-1}$ , respectively) by Salerno et al. (2015),  
 232 calculated using several stations on Koshi basin between ~1,000-8,000 m asl. However, we note that  
 233 reported non-linearity in the temperature-altitude relationship in the Khumbu region (Khadka et al., 2021)  
 234 limits the comparability of lapse rates calculated across different elevational ranges.

235 *Table 2. Mean seasonal and annual Temperature (°C) and precipitation (P, mm) at PH and BC AWSs and the calculated*  
 236 *Temperature and precipitation gradients (TG and PG) between these AWSs.*

Season	Base Camp (BC)		Phortse (PH)		TG (°C km <sup>-1</sup> )	PG (mm km <sup>-1</sup> / % km <sup>-1</sup> )
	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)		
Winter	-8.8	27	-2.1	56	-4.5	-20/-73
Pre-Monsoon	-4.5	87	3.6	115	-5.4	-19/-22

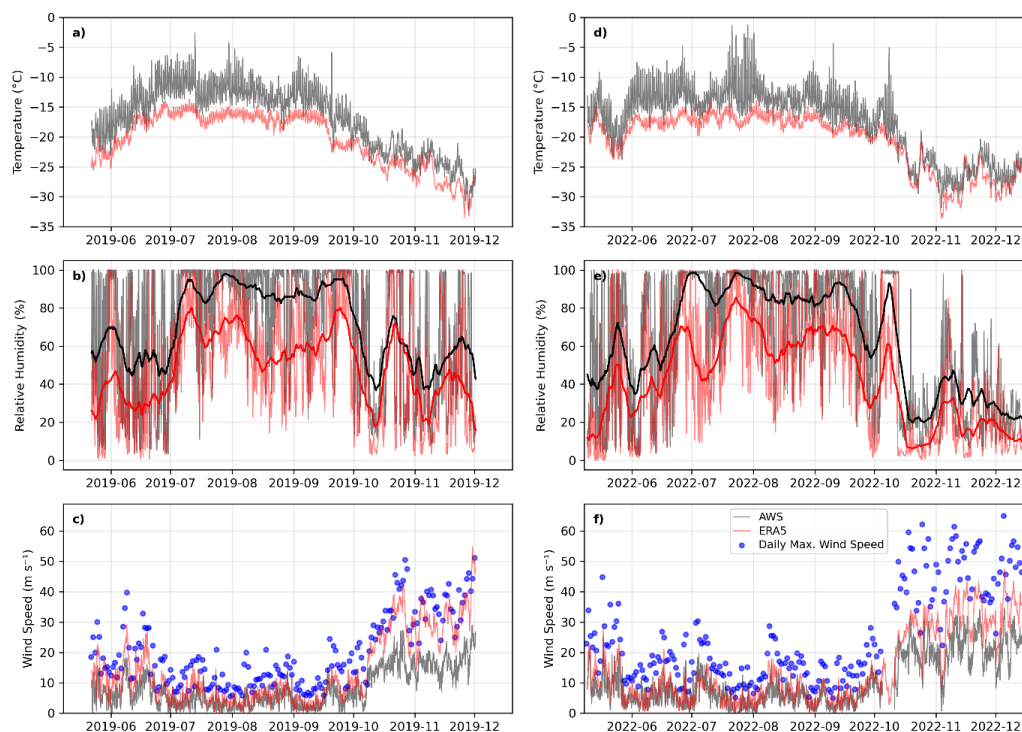


Monsoon	2.4	484	9.7	567	-4.8	-56/-12
Post-Monsoon	-3.1	31	3.9	51	-4.6	-13/-44
Annual	-3.1	629	4.1	790	-4.8	-107/-17

237

## 238 5. Comparison with ERA5

239 Monitoring the meteorology at the highest altitudes in the Himalaya at elevations where glaciers are  
 240 accumulating mass, and where mountaineers are most at risk from extreme weather provides the greatest  
 241 test to observational efforts. Accordingly there is considerable interest in using reanalysis data to extend  
 242 brief in-situ records. However, to facilitate such extensions, it is necessary to establish the extent to which  
 243 such reanalyses products can reproduce the observed meteorology (Khadka et al., 2022). Here, we therefore  
 244 compare temperature, relative humidity and wind speed between the SC AWS (the longest record from  
 245 above Camp II, where extreme weather poses the greatest risk for mountaineers) and ERA5 reanalysis  
 246 (Hersbach et al., 2020) data from the nearest grid point at the 350 hPa pressure level (most representative  
 247 of the SC: mean air pressure 2019-2021 = 377 hPa).  
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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 dark black and red relative humidity line represents the 10 days running mean values.

254 During both 2019 and 2022, air temperature exhibited reasonably close co-variation between the SC  
 255 observations and ERA5, with an  $R^2 > 0.6$  (Figure 4 and Table 3). ERA5 systematically underestimates air  
 256 temperature relative to measurement, although some of that reflects the higher altitude (lower air pressure)



257 at 350 hPa relative to the SC data. Diurnal variability is also considerably greater in the SC dataset (Figure  
258 S3 and S4), likely reflecting diurnal fluctuations in the measured surface heat fluxes at SC, which are  
259 missing in ERA5 as this (higher altitude) pressure level is representative of the free atmosphere.

260  
261 The  $R^2$  (0.49 and 0.57) between the AWS and ERA5 relative humidity were adequate for both 2019 and  
262 2022, however the MAE and RMSE for the relative humidity are  $>20\%$ . From the 10 days running mean  
263 both AWS and ERA5 relative humidity clearly shows the seasonal transitions. In 2019 and 2022 the  
264 monsoon onset was 1<sup>st</sup> July and 14<sup>th</sup> June at SC.

265  
266 In both years the wind speed exhibited the highest correlation between SC observations and ERA5 ( $R^2 =$   
267 0.70). However, ERA5 consistently overestimates mean winds at the SC (MAE = 4.8 and 5.4  $\text{m s}^{-1}$  in 2019  
268 and 2022, respectively (Table 3 and Figure 4). This is again consistent with the ERA5 grid point being  
269 representative of the higher-altitude free atmosphere; frictional drag at the SC reduces the wind speed. We  
270 also observe faster winds in the post monsoon in 2022 compared to 2019.

271 Based on the generally good agreement between ERA5 reanalysis data and observations at the SC, we  
272 anticipate that the reanalysis could be used to gap-fill and extend intermittent meteorological records from  
273 Mt. Everest's upper slopes—correcting the time-varying biases using empirical-statistical, or machine-  
274 learning based approaches (Van Wyk de Vries et al., 2024; Potocki et al., 2022).

275  
276 *Table 3. Values of each statistical metrics ( $R^2$ , MAE, RMSE) obtained by the comparing the SC AWS measured and ERA5 350 hPa*  
277 *temperature (T), relative humidity (RH) and wind speed (WS) at hourly scale for 2019 and 2022.*

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

278  
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## 6. Research Insight | Importance of the data

280 Observations from the SC (Figure 4) highlight the potential for mean winds exceeding 30  $\text{ms}^{-1}$  and gusts  
281 above 60  $\text{ms}^{-1}$  speeds that can be extremely dangerous for mountaineers: at high risk of being blown over,  
282 and elevated the probability of cold injury (Sherpa et al., 2023; Van Wyk de Vries et al., 2024). Elsewhere,  
283 data from the network of AWSs described here has shown oxygen availability at the summit to be highly  
284 variable at synoptic timescales, meaning that the “apparent elevation” of Mt. Everest (how high the  
285 mountain would feel for those not breathing supplemental oxygen) can vary by almost 750 m, and that  
286 during the most challenging winter conditions an ascent without the aid of supplemental oxygen might be  
287 impossible (Matthews et al., 2020b). Accurately forecasting wind speeds and oxygen variability for the  
288 upper slopes of Mt. Everest is therefore of high importance for increasing safety on the mountain. The data  
289 from the AWSs provided here provide the foundation to achieve such improvements. At the minimum, they  
290 can be used to assess uncertainty in the freely-available forecasts widely used by expeditions (Matthews et  
291 al., 2020b); but they can also be used to train model output statistics including novel application of machine  
292 learning to provide improved, hyper-local forecasts for identifying optimal climbing windows (Van Wyk  
293 de Vries et al., 2024).

294 The AWS data shared here can also be extremely useful for understanding cryosphere-climate interactions  
295 at the highest elevations within HMA. For instance, the archive has already been used to estimate the surface  
296 energy balances at the summit of Mt. Everest (Matthews et al., 2020a), and for the South Col Glacier (at  
297  $\sim 8,000$  m asl), revealing a high-altitude system that might be acutely sensitive to changes in effective



298 precipitation due to extremely high levels of insolation(Matthews et al., 2020a; Potocki et al., 2022; Brun  
299 et al., 2023). Yet significant uncertainties remain, not least because the observational record presented here  
300 is brief. Understanding here could be improved through extending these observations with downscaled  
301 reanalyses products (such as ERA5).

302 The data here are useful not only for assessing cryosphere-climate interactions at extreme elevations but  
303 could be used to improve understanding of surface energy and mass balances within the ablation areas of  
304 the region’s glaciers, and below. The precipitation measurements, for instance, are particularly high quality-  
305 -taken behind double Alter shields to reduce under-catch (which likely accounts for the greater  
306 accumulations relative to nearby stations without such shields: Pheriche and Pyramid), and hence offer a  
307 valuable opportunity to constrain mass inputs. More generally, when used in combination with the generally  
308 lower-altitude observations from the GLACIOCLIM and EvK2CNR networks, the data shared here can  
309 improve quantification of elevational gradients in key meteorological variables needed in distributed (e.g.,  
310 glacier or hydrological) modelling assessments across up to approximately five vertical kilometres, and  
311 hence the entire glacierised elevational range of the Khumbu region.

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

319 Ultimately, though, these data might be used in ways far beyond the illustrations above. The upper slopes  
320 of Mt. Everest represented the last frontier for human exploration, reached successfully by humans 42 years  
321 after the South Pole was attained. Meteorological measurements from the highest reaches only began in  
322 2022 (at the BR). We are still, therefore, at the very beginnings of exploring the weather of this extreme  
323 environment, and the list of questions that these data might help answer from disciplines beyond the climate  
324 sciences (e.g., biology: Dragone et al., 2023) might conceivably grow rapidly.

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331 installation and maintenance of the AWSs possible.

## 332 **Authors Contribution**

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



### 338 **Data availability**

339 The quality controlled data is available at: <https://doi.org/10.5281/zenodo.18849098> (Khadka, 2026)  
340 moreover the data in csv format and can be downloaded from  
341 <https://www.nationalgeographic.org/projects/perpetual-planet/everest/weather-data/>.

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