

## Response to Referee #2 (ESSD-2026-183)

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

We thank Referee #2 for their comments and suggestion which significantly helped to improve the manuscript. We have reviewed all the feedback carefully and incorporated clarifications and corrections where requested. All points raised have been addressed in the revised manuscript.

Below, we provide a point-by-point response to all comments raised by the reviewer. The comments are in *italics*, our response is in blue text and the proposed changes to the manuscript are provided in red text. Note that all proposed changes have been incorporated into the revised manuscript and the supplementary material.

### Comments R2:

*The Authors present six new weather stations installed in the Khumbu region (Nepal) between 2019 and 2022, five of them installed between 5000m and 8810 m a.s.l. along the way to Mt Everest. Data are available on Zenodo, updated to May 2025 (last accessed 25/05/2026). After describing location, measured variables, and data treatment, the authors present the two lowest stations (Phortse 3840 m a.s.l.) and Base camp 5315 m a.s.l.) temperature and precipitation seasonality, as well as temperature seasonality at Camp II (6464 m a.s.l.). South col station (7945 m a.s.l.) hourly air temperature, relative humidity, and wind speed are then compared with the ERA5 free-atmosphere 350 hPa pressure level. Associated mean diurnal cycles are reported in the supplementary.*

*Those data represent an impressive effort and are of high interest for both Everest expeditions and scientific knowledge of very high altitude meteorology. The paper is globally well written, and the figures are clearly presented. I think data from the two highest stations (Balcony, 8430 m a.s.l., and Bishop Rock, 8810 m a.s.l.) should be presented (even if spares) to better appreciate their potentialities, also because those stations represent a unique effort. The new network could also be better contextualized within the existing ones to further show its potential in combination with existing data.*

We completely agree. We revised the manuscript to include and discuss the available data from the Balcony (BA) and Bishop Rock (BR) stations, even though they are sparse due to the extreme environmental challenges. This will better showcase the unique nature and potential of these very high altitude measurements. Additionally, we have updated Figure 1 to explicitly show and contextualize our network alongside existing networks from EvK2CNR and GLACIOCLIM.

Figure 3 shows the monthly precipitation and temperature (from December 2019 to November 2022; **Figure 2**) for PH (3,840 m) and BC (5,315 m), the two AWSs in the network that include measurements of precipitation and the monthly mean, minimum and maximum temperature from all the available data from SC, BA and BR AWS sites. Whilst this is a very short period for understanding climate variability, there is a clear seasonal pattern in precipitation and temperature at both sites. The annual precipitation is 790 and 629 mm, with 72 and 77% of this falling during the monsoon at the PH and BC AWSs, respectively. The

average annual 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 (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 (max 7.8 °C in March, min 3.6 °C in December), respectively. Based on the available data, at higher sites (above CII AWS), July is the warmest month (Figure 3). From the South Col it is found that the mean temperature during the July is -12.2 °C with 10.2 °C diurnal variation, where as February is the coldest month (-29.7 °C) with 4.4 °C diurnal variation.

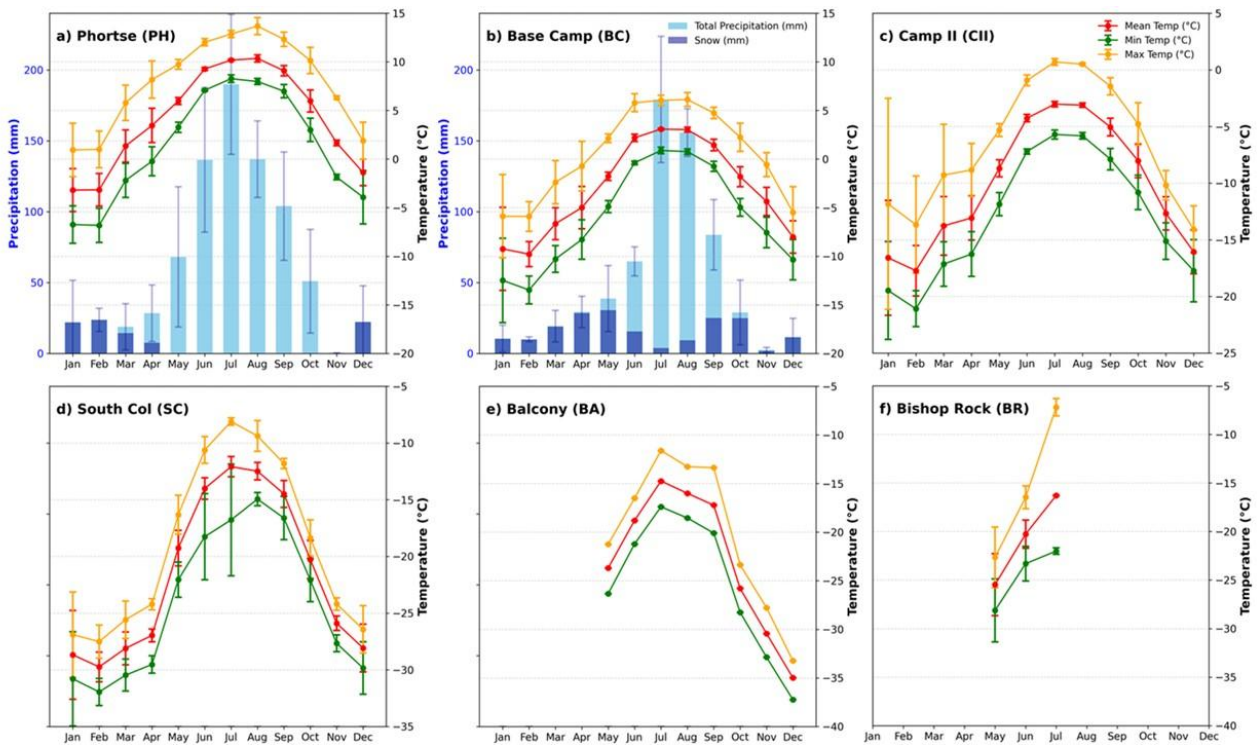


Figure 1. Mean annual cycle of monthly precipitation (snow and total precipitation in mm liquid water equivalent, histograms) and monthly mean, minimum and maximum air temperature (T, lines) during December 2019- November 2022 at PH, BC and CII AWSs (a, b, c) and monthly mean, minimum and maximum temperature for all the available period for SC, BA and BR AWSs (d, e, f). The bar represents the monthly standard deviation for all different variables.

L28 Seasonal climatology is presented only for three of the six stations

Thank you for pointing this out. Now we have added the missing point to make it clear and also the other stations are added along with the figure 3 and explained in the text.

“Here we present quality controlled (QC) meteorological data from six AWSs 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 for the lower three AWSs, and a comparison with ERA5 reanalysis data from the South Col AWS.”

L53 EvK2CNR network data is available at <https://essd.copernicus.org/articles/17/4293/2025/> and should be cited here

Thank you for the suggestion; Salerno et al., 2025 is added now

L83 and Figure 1. The authors should choose between reporting all AWS installed in the Khumbu or only the ones presented in this paper. The current mixed solution creates confusion. In my opinion, it would be a nice added value for the new AWS to be contextualized within the existing networks (EvK2CNR and GLACIOCLIM as presented in L51 to L58). I would thus suggest reporting in Figure 1 all existing/published AWS (e.g., with different colors for each network), distinguishing between still active and dismissed stations.

Similar to the response to R1: Thank you for this very good suggestion. Now we have added the operational GLACIOCLIM and EvK2CNR network in the Figure 1.

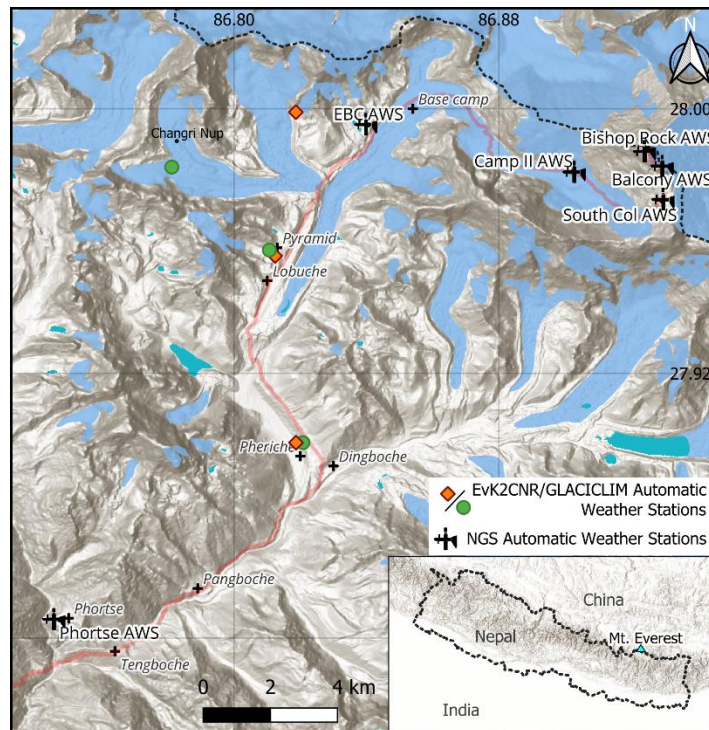


Figure 2. Geographical location of different automatic weather stations (black symbol) installed during the National Geographic (NGS) Rolex Perpetual Planet Everest expeditions 2019-2022 along with other operational stations by EvK2CNR and GLACIOCLIM, in the Khumbu region of Nepal. The plus symbol represents camps in the valley including Everest Base Camp and the Changri Nup point is the area where Meteorological glaciological observation has been monitored since 2010 and the red lines represents the normal climbing route to Mount Everest from South side.

L95-96 It would be nice to see a comparison of wind measurement with traditional and pitot sensors

Thank you so much for highlighting the importance of comparison of the different wind measurements. However, given the significant extra text and at least one figure(s) that this would require, we prefer to address this in another piece of work. Indeed, we have performed this comparison in another piece of work (currently under review in the *Bulletin of the American Meteorological Society*, 'BAMS'). We do not wish to replicate this here. We do, however, now summarize the relationship between wind speeds measured by these sensors and we reference the BAMS paper under review.

*L118 considered reformulating "detail measurement details"*

Thank you, now we corrected it.

"Below, we **provide** measurement details for the respective meteorological variables. This information is also summarised in Table 1."

*L128 please explain the limitations that conduct to install temperature and humidity sensor at 1.5m in higher stations.*

Thank you, we added the reason to install that at 1.5 m

"The sensors are installed 2 m from the ground for the lower AWSs (PH, BC and CII), and 1.5 m for the higher 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 the station breaking or blowing over during severe wind gusts.**

*L153. Please comment the installation of the optical disdrometer and the snow level sonic sensor (table 1), and how it may help to validate precipitation data in case of a lack or insufficient antifreeze agent.*

Similar to the response to R1: We thank the reviewer for this valuable suggestion. In response, we have added a description of the optical disdrometer and snow-level sonic sensor to the manuscript Section **2.1.5 Precipitation**. These instruments were installed to complement the precipitation measurements and support additional analyses. The disdrometer provides information on precipitation particle size and intensity, while the snow-level sensor helps identify snow occurrence and surface conditions, improving the overall interpretation and validation of precipitation data. However, we note that the SR50 and disdrometer data have not been analysed in this study, as the present work does not focus on these specific datasets.

"An optical disdrometer (OTT Parsivel<sup>2</sup>) and a snow-level sonic sensor (SR50A) were installed to complement the precipitation measurements. However, because these instruments require highly specialized data filtering (e.g., for wind noise and blowing snow) and our current study focuses strictly on baseline

meteorological dataset, these datasets are not analyzed here and will be presented in future work (Table1; Löffler-Mang and Oceanic, 2000; Ryan et al., 2008).”

*Table 1 why snow level and disdrometer has not been described in the text?*

Now we have added the very short description as mentioned in the response of previous comment.

*L114 an estimation of the approximate weight has been given for the lower station. (Report m a.s.l. for elevation)*

We have added the elevation and name of the AWS to make it clear about the lower and higher AWSs.

“The overall weight of the lower AWSs (PH, BC, and CII; < 6500 m asl) is approximately 60 kg and the upper AWSs (SC, BA, BR ; > 6500 m asl) weigh 52 kg, including the additional pitot tube (~2 kg) and other sensors added in 2022 (Matthews et al., 2020, 2022).”

*L189-191 I am curious about wind speed measured with pitot sensor. Are the data available to cross-check the traditional wind sensor freezing event?*

As responded before, we have compared the wind speed measured by different sensors in an another paper which is under review at BAMS.

*L195-199: Please explain why you expect a SWin underestimation rather than SWout overestimation in the case of albedo > 0.95? (check typo L198 , “95 (Shea et al. 2015; [...])”)*

Usually during early mornings with fresh snow or deposition at the top of the sensors, we can see these kinds of underestimation. There are no specific ways to correct that except the way developed by Shea et al. 2015. So, we followed the similar way from Shea et al. 2015 to correct it for the quality control

**“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 (SWin), while the downward-facing sensor continues to accurately measure the outgoing shortwave radiation (SWout) of the fresh snow surface. Consequently, the calculated surface albedo ( $\alpha = SWout / SWin$ ) 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 SWin values during these specific cases. Specifically, for periods where the calculated albedo exceeded 0.95, it was assumed that SWin was underestimated (e.g., due to sensor riming or a tilted sensor). SWin was recalculated as  $SWout / 0.95$  to provide a more realistic estimate 95 (Shea et al., 2015; Khadka et al., 2022).”

*L200 check typo “pluvio 2”)*

Added OTT before the Pluvio<sup>2</sup> to correctly reflect the manufacturer's trade name.

*L200-203 Any check on missed snowfall due to potential issues with antifreeze agent? Do the authors consider potential cross-check with snow level and disdrometer data (especially for base camp station)?*

No, we did not find any missing snowfall due to antifreeze issues, and we have not performed this cross-check in this paper.

Because the OTT Pluvio<sup>2</sup> is a weighing-type precipitation gauge, it records precipitation by continuously measuring the actual mass of the snow or rain that falls into the bucket. The antifreeze agent is only used to keep the collected water from freezing solid and damaging the bucket; it does not change how the gauge measures mass. Since the total weight is recorded automatically regardless of freezing, we do not expect any missed snowfall events.

*Figure 2 has not been recalled in the text. Consider moving the text (e.g. “a) temperature and relative humidity”) outside of the panels and enlarge line thickness for better visibility, especially for BR and BA stations (also consider avoiding the “intense” yellow for BA to improve readability)*

Thank you for the very good suggestions.

Now the Figure 2 is cited in the Section 3 and 4. Additionally the figure is modified as your suggestions

*L109-216 and figure 3: Please add available data for SC, BA, and BR even if the data are very sparse. Also, consider adding and discussing radiative seasonality.*

We have updated Figure 3 to include the sparse data distributions for South Col (SC), Balcony (BA), and Bishop Rock (BR).

We also added the mean daily radiative plot in the supplementary and highlighted the seasonal and altitudinal variation.

*“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 stays high throughout the monsoon season. Notably, the maximum daily LWin at PH during the monsoon goes over  $350 \text{ Wm}^{-2}$ , while at SC it stays below  $\sim 250 \text{ Wm}^{-2}$ . This big difference highlights how much colder the air is at higher altitudes. 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).”*

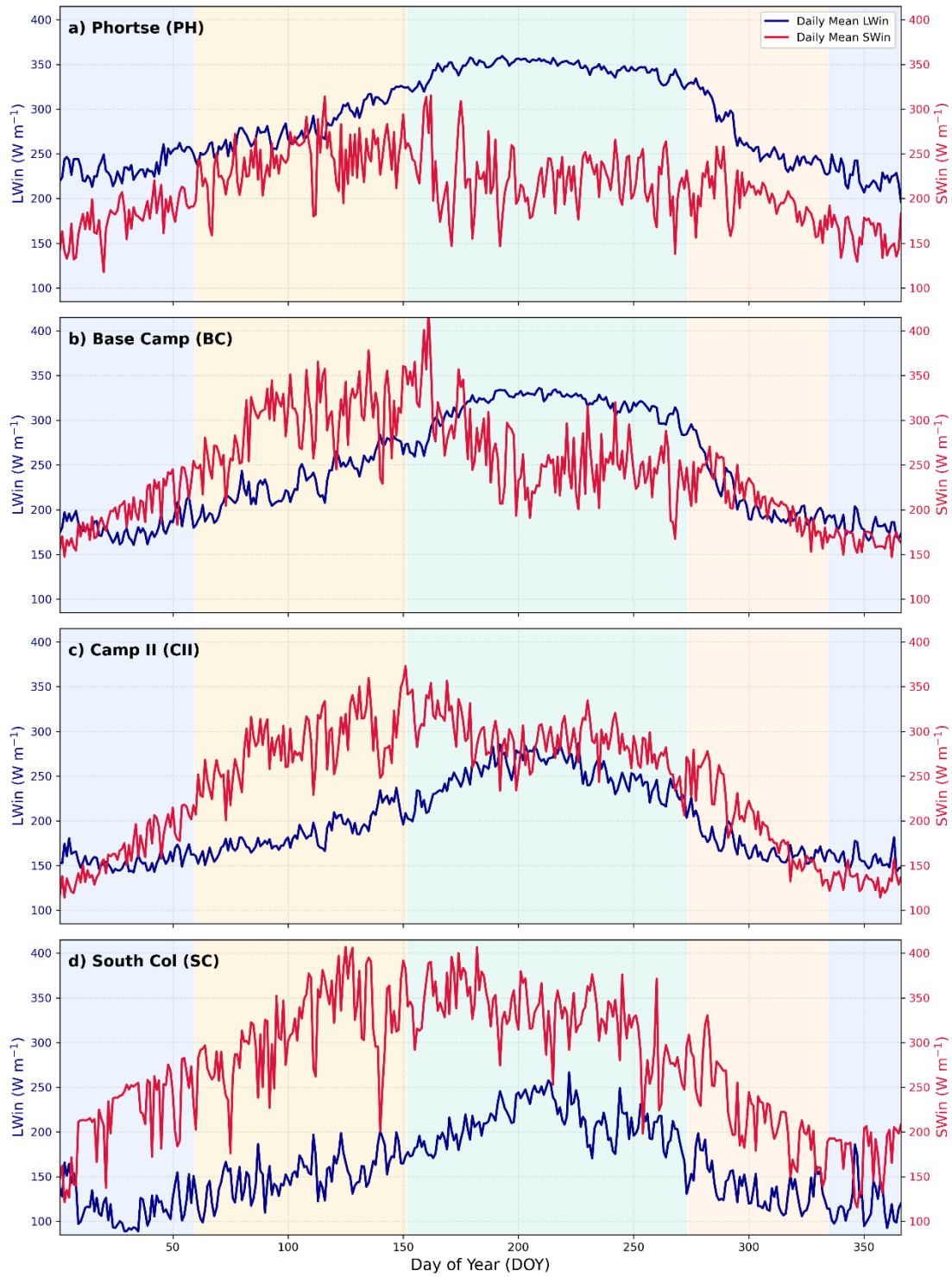


Figure S 1. Mean annual cycle of incoming longwave radiation (LWin) and shortwave radiation (SWin) at PH, BC, CII and SC AWSs from all the available data.

*L224 Please specify that -107 mm/km refers to the mean annual precipitation. In addition, considering that the wide majority of precipitation occurs during the monsoon, maybe the monsoon gradient is more significant?*

We have clarified in the text that -107 mm/km is the mean annual gradient. Interestingly, the monsoon precipitation gradient is actually less steep -56 mm/km than the annual average, despite the monsoon bringing most of the annual rainfall. This occurs because non-monsoonal precipitation (winter, pre-monsoon, and post-monsoon) drops off much more sharply with altitude.

“Seasonal mean values, and elevation gradients between the Ph and BC AWSs (separated by ~1500 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 location. Calculated as a single derivative across this span, the mean annual precipitation gradient. The precipitation gradients average -107 mm km<sup>-1</sup> (-17 % km<sup>-1</sup>) average over three years, but it declines by almost 50 % during the monsoon (to -56 mm km<sup>-1</sup>/12 % km<sup>-1</sup>). This 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.”

*L228-234 Consider also using temperature from the other stations and plotting the seasonal mean value for each pair of stations so that non-linearity in temperature gradient can be appreciated. While it is easily understandable that precipitation measurement is limited to base camp, it is a pity to present a network ranging from 3800 to 8800 meters but reporting the temperature gradient only between 5300 and 3800.*

We completely agree with the reviewer that restricting the temperature gradient analysis to the lower two stations misses an excellent opportunity to showcase the full potential of this unique elevational transect. In Table 2, Figure S3 and in the text, we therefore now show the TG from all four stations in both linear values as well as non linear equations. Which might be very much useful to cryosphere research in future.

“Seasonal mean values, and elevation gradients between the Ph and BC AWSs (separated by ~1500 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 location. Calculated as a single derivative across this span, the mean annual precipitation gradient. The precipitation gradients average -107 mm km<sup>-1</sup> (-17 % km<sup>-1</sup>) average over three years, but it declines by almost 50 % during the monsoon (to -56 mm km<sup>-1</sup>/12 % km<sup>-1</sup>). 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 the both (PH and BC) observing sites is higher than the amount measured at the Pheriche (4200 m asl: 540 mm (Nov 2016-Dec 2020)) and Pyramid (5050 m asl: 449 (EvK2CNR: 1994-2012) and 591 mm (Nov 2016-Dec 2020)) by IRD stations (Khadka et al., 2022; Salerno et al., 2015). Similarly, between the PH and BC, the mean temperature gradient (TG) is -4.8 °C km<sup>-1</sup> with minimum -4.5 °C km<sup>-1</sup> during the winter and maximum -5.4 °C km<sup>-1</sup> during the Pre-monsoon. 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 the all four stations (Table 2) are higher negative (pre-monsoon, monsoon, annual: -6.5, -5.7, -6.0 °C km<sup>-1</sup>, respectively) than the values previously reported by Salerno et al. (2015) and Graves et al. (2026), calculated using several stations on Koshi basin betw (1,000-8,000 m asl) and and Dudhkoshi basin (2,600-8,400m asl). However, the TG calculated from the all four AWSs (Table 2) is comparable in both and annual scale 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 present a non-linear equation for the temperature gradients between Ph and SC, which serves as a critical tool for future high-elevation precipitation phase and glacier modelling.”

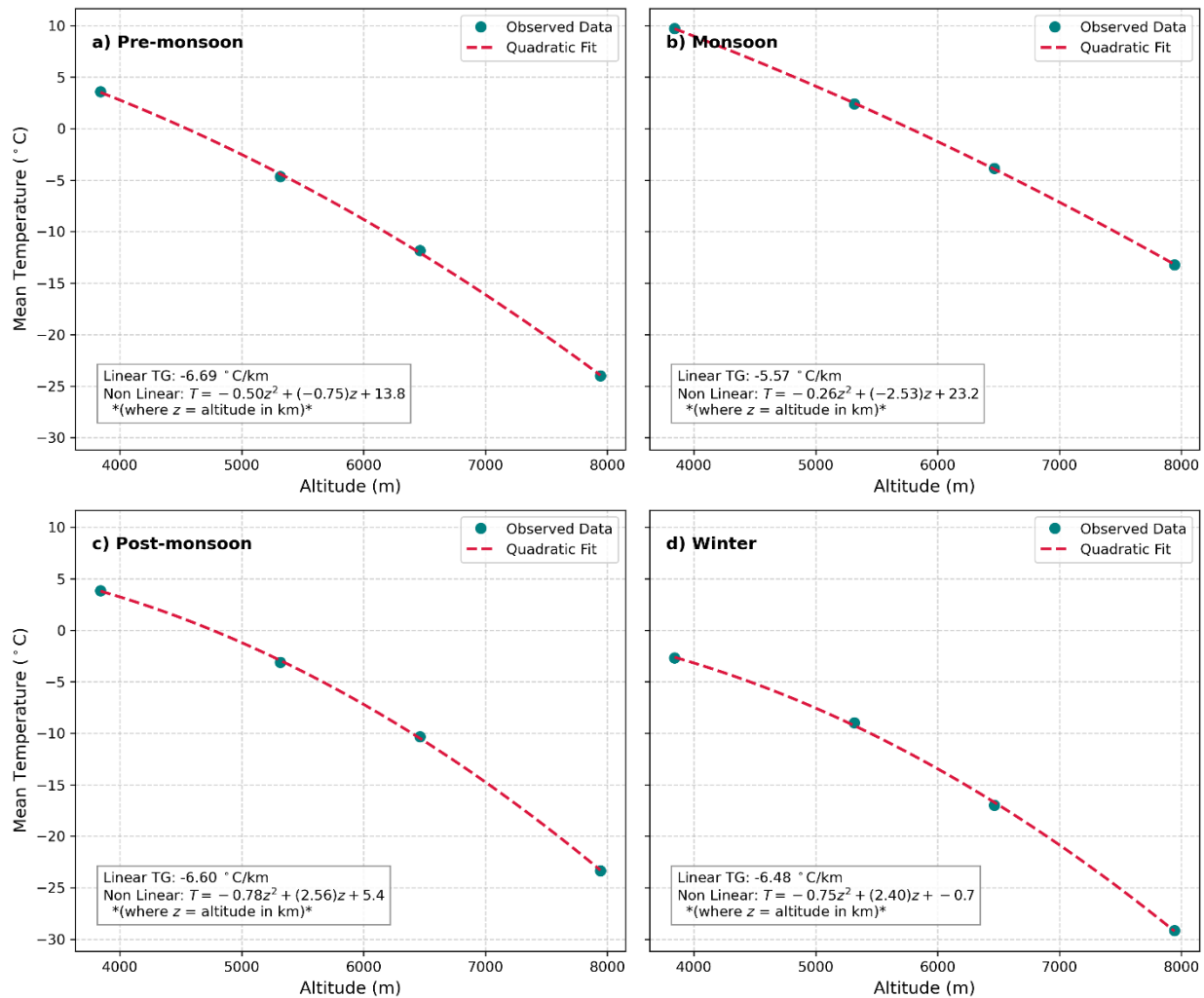


Figure S 2. Linear and Non-Linear temperature gradient (TG) calculated using the mean seasonal temperature from four different AWSs (PH, BC, CII and SC) for the period of Dec 2019 to Nov 2022)

Table 2. Specify the definition used for winter, pre monsoon, monsoon and post-monsoon aggregation

Now the months are also added to define the specific season

*L239-247 and figure 4. It would be interesting to also report available data from BA and BR. It will help the reader to make its own opinion on how local station can be representative of larger-scale (0.25°\*0.25°) era5 node and further support the affirmation L271-274.*

We have modified Figure 4 to incorporate the available data points from BA and BR against the corresponding ERA5 free-atmosphere levels. Also added the text to support the findings

*“To further assess the representativeness of ERA5 at high elevations (0.25° × 0.25° resolution), we compared ERA5 temperatures with shorter observational records from BA and BR. In 2019, the correlation (R<sup>2</sup>) between ERA5 and BA found 0.85, while in 2022 the R<sup>2</sup> between ERA5 and BR was 0.56. Despite the shorter datasets, these results indicate that ERA5 temperatures at 350 hPa provide a reasonable representation of atmospheric conditions in data-sparse, very high-altitude regions.”*

*Figure 4. Specify if the daily max (blue dot) is from SC observation or ERA5.*

The daily max wind speed in the caption of figure 4 is defined. Thank you!

We thank the referee for pointing this out. We have update the caption of Figure 4 to explicitly state that the daily maximum wind speed (blue dots) represents the SC observation data, not the ERA5 data.

*L256 Temperature gradient between SC, BA, and BR may help to downscale ERA5 temperature at actual SC elevation?*

We appreciate the ideas form the referee. We considered this point during the preparation of the study; however, due to limited data availability at SC, BA and BR, we were unable to obtain consistent temperature gradients throughout the year, which could affect the comparison. Therefore, we believe that proceeding without downscaling is more appropriate for maintaining a consistent comparison.

We thank the referee for this good point. We agree that calculating a changing lapse rate is possible. However, we want to clarify that the goal of this section is to see if the weather station and the ERA5 data move up and down together over time (co-variation). We are not trying to match their exact, absolute temperature numbers. Fixing the elevation difference would shift the absolute temperatures up or down, but it would not change how well the two datasets track together over time. Therefore, we believe leaving the data without downscaling is the best choice for this specific comparison.

*L283 Specify that this is based on atmospheric pressure data*

Specified

*L289 consider to reformulate “[...] provided here provide [...]”*

Reformulated

*L300 check sentence*

Corrected

*L307-311 I fully agree; Presenting the full networks in Figure 1 would be nice.*

Thank you, now we have added the EvK2CNR and GLCIOCLIM network in the Figure 1

*L 340 check sentence “[...]the data in CSV format and can”*

Corrected

**We believe these revisions address all concerns raised by the referee and significantly strengthen the manuscript. Thank you again for your time and expertise.**