Mount Everest's photogenic weather during the post-monsoon

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Mount Everest, known locally as *Sagarmatha* or *Qomolangma*, is the world's highest (8849m), and arguably most iconic, peak. That allure draws large numbers of tourists to Nepal every year with hopes of seeing or climbing the famed mountain. Importantly, the large tourist presence has wide ranging environmental (Napper *et al*., 2020; Aubriot *et al*., 2019; Semple *et al*., 2016; Faulon and Sacareau, 2020; Miner *et al*., 2021; Byers, 2005), cultural (Rai, 2017; Nepal *et al*., 2020), societal (Pallathadka, 2020; MOFA, 2021) and economic (Nyaupane, 2015; Mu, 2019) implications for the Khumbu Region of Nepal. Using data from a new array of automatic weather stations (AWSs) installed as part of the 2019 National Geographic and Rolex Perpetual Planet Everest Expedition (Matthews *et al*., 2020a,b) showed that seasonal variations in the weather on Mt. Everest modulates the timing of optimum climbing conditions for mountaineers. However, the influence of seasonality on the likelihood of visitors' ability to view the famed summit from Mt. Everest's (Nepalese) Base Camp has not been assessed. Here, we utilize previously unpublished photos taken twice-daily by an automatic camera at the Base Camp AWS (Figure 1), alongside meteorological data, to examine the impacts of weather on the visibility of this iconic peak that draws visitors from all over the world.

Using the seasonal timing identified by Matthews *et al*. (2020a), we investigate the conditions of both the 2019 and 2020 post-monsoon seasons (1 October to 30 November) using hourly measurements from five AWSs, at varying altitudes, along the Mt. Everest summit route (Figure 2a): Phortse (3810m), Everest Base Camp (5315m), Camp II (6464m), South Col (7945m) and Balcony (8430m). Here, we examine data encompassing two post-monsoonal seasons, from 1 August 2019 to 31 January 2021, the time periods when the upper slopes of Mt. Everest are least obscured by clouds. In addition to the numerical data recorded by the AWSs, a Campbell Scientific Canada CCFC Field Camera looking eastward toward the summit of Mt. Everest was also installed at Everest Base Camp during the 2019 Everest Expedition (Figure 1). As shown in Figure 2(a), the camera's viewshed from left to right (north to south, respectively) primarily shows Mt. Everest's West Ridge (~7000–7200m), Mt. Everest's summit (8849m) and Nuptse's sub-peak (~7400m). The camera takes two photographs daily at 0937 Nepal time (NPT) (0352 UTC) and at 1437 NPT (0852 UTC), respectively.

According to meteorological data, the summer monsoon brings significant changes to the Nepal Himalaya (Khadka *et al*., 2021), and herein, we show that the monsoon's departure brings equally significant changes once more. One noticeable difference is the absence of cloud cover during the post-monsoon season, as suggested by AWS measurements of incoming shortwave radiation and downward

Figure 1. The Everest Base Camp automatic weather station (5317m; 27.9952°N, 86.8406°E). Camera is 1.5m off the ground. Photo was taken on 26 May 2019 at 1158 NPT (0613 UTC). Photo credit: Baker Perry.

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(a)

(b)

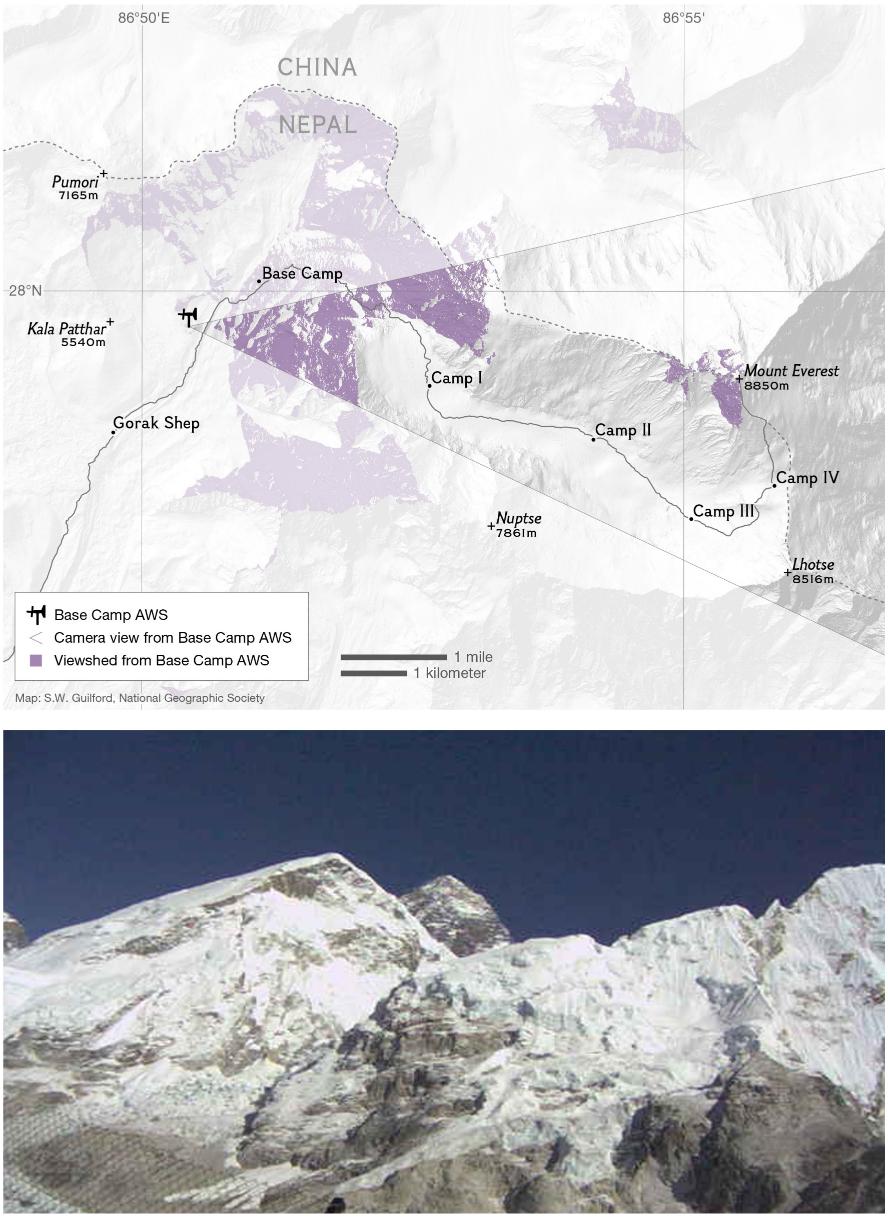

Figure 2. (a) Viewshed of the Everest Base Camp camera and (b) sample photo from Everest Base Camp camera during the 2019 post-monsoon. Photo was taken on 14 October 2019 at 1437 NPT (0852 UTC). Photo credit: @Ever_Weather/National Geographic Society.

longwave radiation measured by the Camp II AWS (Figures 3a,b). Using the mean daily values for incoming shortwave and downward longwave radiation with a three-day running mean (Figures 3a,b), we can assess trends across seasonal changes for both 2019 and 2020. The transition from the monsoon to post-monsoon season shows an increase in incoming shortwave radiation accompanied by a decrease in downward longwave radiation.

Downwelling longwave is a function of the emissivity and temperature of the atmosphere. We separate these by computing the thermal emissivity of the surrounding air at Camp II located 2m above the surface using the Stefan–Boltzmann Law for a grey body:

$$\varepsilon = j^{*}/\left(\sigma T^{4}\right) \quad (1)$$

where j^* is the mean daily downward longwave radiation in Wm^{-2}, ε is the thermal emissivity of the surrounding air, σ is the Stefan–Boltzmann constant approximated to 5.67E-8Wm^{-2} and T is the mean daily air temperature (Kelvin) recorded at the Camp II AWS in Kelvin. Without an airborne device to record air temperature at cloud level, the 2m air temperature serves as an approximation for this. The three-day running mean of emissivity in Figures 3(c) and (d) shows a post-monsoonal drop in both years assessed. In 2019, the decline in emissivity was from 0.87 (±0.09, where uncertainty is one standard deviation) to 0.68 (±0.11); in 2020, the decline was from 0.82 (±0.11) to 0.62 (±0.07). Accompanied by the uptick in shortwave radiation, this drop suggests a lack of cloud, which would re-radiate longwave radiation back down towards the surface.

In support of the meteorological data, images collected from Base Camp looking towards the summit, which first became available on 11 October 2019, confirm an absence of post-monsoonal cloud cover. Figures 4 and 5 each contain five 32-day photo arrays depicting the seasonal changes in morning and afternoon cloud cover, respectively. Through manual assessment, these arrays show that the clouds enshrouding Mt. Everest during the monsoon season are replaced with clearer skies as the post-monsoon progresses. Of note, cloud coverage tends to increase into the afternoon when compared with the morning, especially during the monsoon season as shown by the differences between Figures 4(e) and 5(e). During the post-monsoon, afternoons also tend to be cloudier than mornings, but the diurnal variation is less pronounced than during the monsoon (Figures 4c and f; 5c and f). More photographic data from future years are needed to confirm this. Depending on the season, trekkers and climbers may want to be in line of sight of the peak earlier in the day should their goal be to see Mt. Everest's summit.

We also monitored the changes in relative humidity (RH) at the Phortse, Base Camp, Camp II, South Col and Balcony AWSs for 2019 and the lower four stations for 2020 using the mean daily RH with a three-day running mean shown in Figures 3(e) and (f). The change in season from the monsoon to post-monsoon is accompanied by a significant drop in RH (Figures 3e and f) as the regional winds shift direction from off the Bay of Bengal and Arabian Sea to more westerly continental trajectories (Perry *et al*., 2020). The drop in RH is most noticeable for the higher stations of Camp II and South Col located at 6464 and 7945m asl, respectively. In the 2019 post-monsoon, these stations experience a decrease from an average of around 90% RH to 20% RH over the course of 15 days, with a similar decrease from 80% to 20% observed in 2020, staying below 50% for the majority of the season. While data at the South Col station are missing during the transition to the post-monsoon, the RH is initially close to that at Camp II, so we expect it to have similar values up to and through the monsoon / post-monsoon transition, after which it begins to diverge slightly. Lower humidity post-monsoon is consistent with a decrease in cloud cover at that time.

Another quantity of interest is the specific humidity calculated for each station in both years with a three-day running mean (Figures 3g,h). Of the five stations, the Phortse and Base Camp AWSs see the largest decreases in specific humidity over a short period, from 8.8 to 4.0 and 6.1 to 2.0gkg^{-1}, respectively, occurring at the same time as the similarly large decrease in RH. For both years, the specific humidity

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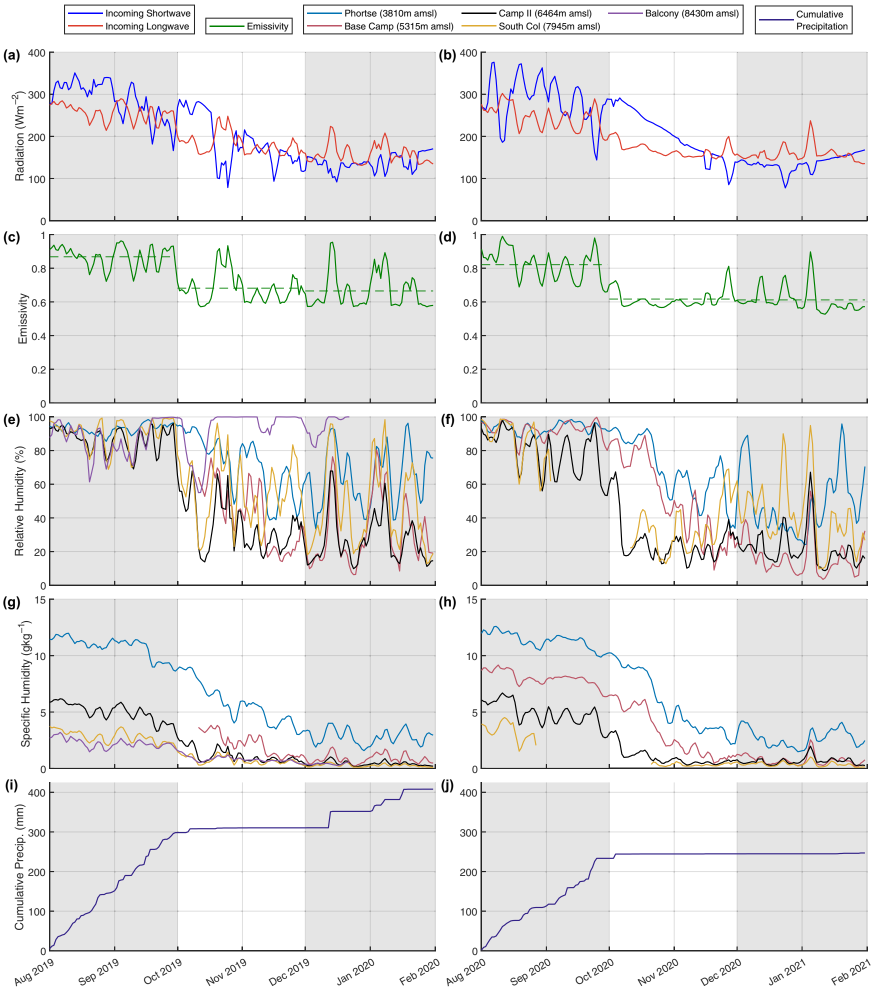

Figure 3. (a, b) Mean daily incoming shortwave (blue) and longwave (red) radiation at Camp II, (c, d) thermal emissivity at Camp II, (e, f) mean daily relative humidity with respect to ice when air temperature is ≤ 0°C and with respect to water when air temperature is >0°C at Phortse (blue), Base Camp (red), Camp II (black), South Col (orange), and Balcony (purple) stations, (g, h) specific humidity at the same stations as for relative humidity, (i, j) cumulative precipitation at Phortse. For each panel, data beginning in the 2019 monsoon is on the left and the same interval from 2020 is on the right. All data are smoothed with a three-day running mean. The shaded regions indicate periods outside of the post-monsoon season (unshaded). The average emissivity for each season is shown by the dashed horizontal line in each region. The Base Camp AWS was inactive prior to 11 October 2019. The South Col AWS is missing relative humidity data starting 4 September 2020 and ending 10 October 2020, and is also missing pressure data for specific humidity starting 27 August 2020 and ending 20 October 2020. The Balcony AWS recorded no temperature or relative humidity data beginning 21 December 2019 due to either sensor or cable failure. There are also no wind speed or direction data from wind sensor 2 (not included in this analysis) beginning 2 January 2020 due to either sensor or cable failure. The last satellite data transmission occurred at 0500 UTC on 20 January 2020 as anchors likely failed on that date. Tenzing Sherpa and Lakpa Sherpa made the first maintenance visit on 12 May 2021 and found the Balcony AWS toppled due to anchor failure. They recovered the datalogger with new data through 10 February 2020 which are appended to the data file, available at: https://www.nationalgeographic.org/projects/perpetual-planet/everest/weather-data/.

approaches its minimum towards the end of the post-monsoon for all stations.

The post-monsoon is also accompanied by a significant decrease in precipitation at Phortse (the only AWS for which precipitation data are currently available), shown by the plateauing of cumulative precipitation at the start of the season (Figures 3i,j). While a lack of precipitation at lower elevations alone may not directly indicate a lack of cloud coverage near the summit, the clear conditions along the lower section of the Nepali route will benefit climbers looking to catch an early glimpse of Mt. Everest.

Compared to the transition from the monsoon to the post-monsoon, the continuation into winter currently provides much smaller but still noteworthy changes in atmospheric conditions. RH shown in Figures 3(e) and (f) continues to decrease and reaches a minimum for the observed time period. The mean emissivity in Figures 3(c) and (d) sees little change, falling from 0.68 (±0.11) to 0.67 (±0.14) for 2019, and for 2020, from 0.62 (±0.07) to 0.61 (±0.09). Specific humidity also remains fairly consistent near the minimum at each station throughout the two-month winter period observed for both years, except for a small peak in 2021 at the beginning of January. Despite the photo arrays in Figures 4 and 5 showing similar cloud coverage to the post-monsoon period, the Phortse AWS recorded more precipitation, especially in 2019, as shown in Figures 3(i) and (j).

We also want to emphasize our limited period of records and that we cannot rule out potential anomalous conditions during this season as big storms limiting visibility can occur during any month under favourable synoptic circulation. Tropical cyclones can also impact the region during the post-monsoon season, as evidenced by the devastating Cyclone *Hudhud* in October 2014 in the Annapurna Region (Simon Wang *et al.*, 2015).

Taken altogether, our meteorological and photographic evidence suggests a relatively cloud-free post-monsoon period on Mt. Everest over the past 2 years, particularly in 2020 with the mean thermal emissivity remaining close to the average of the season for the majority of the period. The resulting high visibility period that we identify herein has large implications for tourism and for the residents of the region. Tourism has been increasing rapidly in Nepal; from 45 970 visitors in 1970 (Neupane *et al.*, 2012) to 1 197 000 visitors bringing Nepal US$714 million in revenue in 2019 (World Bank, 2021a,b), the last year of available data prior to the COVID-19 pandemic, which significantly decreased global tourism (Weissenbach, 2021). As of 2019, 16.5% of tourists to Nepal declared their travel purpose as 'trekking and mountaineering' (MOCTCA, 2020). This explains why the increase in overall tourism is accompanied by a similarly rapid increase in the number of tourists visiting Sagarmatha National Park, which surrounds Mt. Everest's southern flanks, from 3600 visitors in 1979 (UNESCO, 2021) to over 35 000 in 2013 (Baral *et al.*, 2017) and 57 289 in 2019, with almost 43% visiting around the post-monsoon (MOCTCA, 2020). The influx of visitors not only provides much needed financial resources to the Khumbu Region, but also creates stress on the local environment (Byers, 2005; Semple *et al.*, 2016; Aubriot *et al.*, 2019; Faulon and Sacareau, 2020; Napper *et al.*, 2020; Miner *et al.*, 2021). While most climbers attempt to summit in the pre-monsoon season (April/May/June) and 32% of visitors also travel there during this time (MOCTCA, 2020), using meteorological and photographic data, we determine that the post-monsoon season (October/November) offers a markedly better opportunity for trekkers on the Nepali side of the mountain wanting to see – rather than climb – Mt. Everest's summit during this

Figure 4. Daily morning photos taken at 0937 local time (NPT) (0352 UTC) from the Everest Base Camp weather station looking toward Mt. Everest's summit. The photo arrays depict (a, b) clear-sky example photos of the post-monsoon morning on 12 November 2019 and 1 November 2020, respectively, 32 consecutive days of (c) the 2019 post-monsoon season beginning on 16 October 2019, (d) the 2019/2020 winter season beginning on 16 December 2019, (e) the 2020 monsoon season beginning on 16 August 2020, (f) the 2020 post-monsoon season beginning on 16 October 2020 and (g) the 2020/2021 winter season beginning on 16 December 2020. In each array, the first photo is in the upper left corner, with the subsequent 31 daily photos from left to right across each row, in turn.

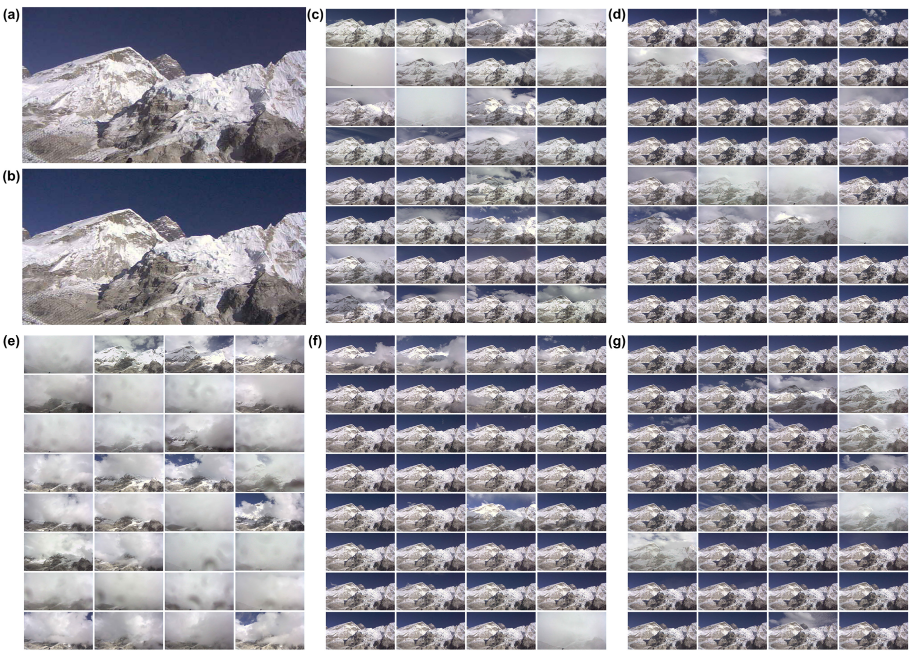

Figure 5. Daily afternoon photos taken at 1437 local time (NPT) (0852 UTC) from the Everest Base Camp weather station looking toward Mt. Everest's summit. The photo arrays depict (a, b) clear-sky example photos of the post-monsoon afternoon on 12 November 2019 and 1 November 2020, respectively, 32 consecutive days of (c) the 2019 post-monsoon season beginning on 16 October 2019, (d) the 2019/2020 winter season beginning on 16 December 2019, (e) the 2020 monsoon season beginning on 16 August 2020, (f) the 2020 post-monsoon season beginning on 16 October 2020 and (g) the 2020/2021 winter season beginning on 16 December 2020. Arranged as in Figure 4.

secondary climbing window. Due to the significantly higher burden of supporting staff and resources required by prospective summit climbers, the pressure of the mountain's workers and the environment during the pre-monsoon climbing season could be significantly reduced if even more trekkers who are seeking to view Mt. Everest, rather than summit, travelled there during the post-monsoon.

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