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# Weather on Mount Everest during the 2019 summer monsoon

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Here we share insights about the arrival of the monsoon at the Earth's highest mountain. Using new high-altitude automatic weather stations (AWSs) deployed on Mt Everest during the *National Geographic and Rolex Perpetual Planet Everest Expedition* in April and May 2019 (Matthews *et al.*, 2020) we show that the monsoon triggers large changes in temperature, humidity and wind with a signal that generally grows with elevation. The largest shift in temperature is inferred for Mt Everest's summit (8849m) where we estimate that warming leads to temperatures not uncommon on much lower mountains in the mid-latitudes during the winter. Our

documenting of the monsoon here is the first in a series of short pieces reporting the progression of the seasons on Mt Everest

The arrival of the summer monsoon is known to signal a progressive and remarkable transformation across the Nepalese Himalaya, characterised by increases in air temperature, cloud cover, and precipitation (Shea *et al.*, 2015). Surface melt accelerates (Litt *et al.*, 2019) and avalanches become more likely, meaning mountaineering becomes increasingly difficult and dangerous (Moore & Semple, 2006). To date, very few people have reached the summit of Mt Everest during the monsoon (Huey & Salisbury, 2003; The Himalayan Database, 2019). The new AWSs on the

mountain therefore offer a glimpse into the weather conditions during this period of the year when the mountain has been largely hidden from the outside world.

Matthews *et al.* (2020) identified the 2019 monsoon as occurring between 1 July and 30 September based on available meteorological data from May to December 2019. The presence of warmer and moister air masses during this period is evident in the observations from the Phortse (3810m), Camp II (6464m), South Col (7945m) and Balcony (8430m) weather stations (Figure 1). Specific humidity rises from 10.0gkg<sup>-1</sup> in June to 11.5gkg<sup>-1</sup> July (a net rise of 15%) at Phortse, but more than doubles at South Col with a rise from 1.5 to 3.3gkg<sup>-1</sup> (a net

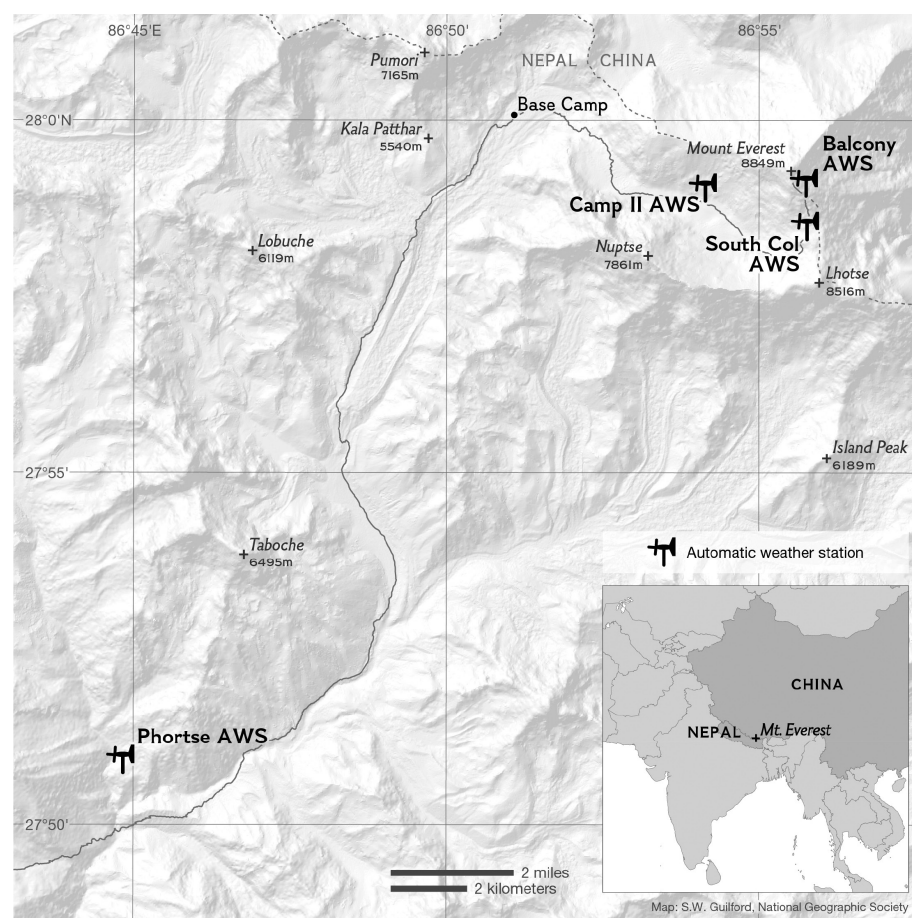


Figure 1. Location of the four new AWSs (black symbols) in the Khumbu region referred in this study. A fifth AWS was placed at Everest Base Camp but was not used in this study because its data were not accessible at the time of writing.

**Table 1**

Mean monthly/seasonal temperature ( $T$ , °C) and specific humidity ( $q$ , gkg<sup>-1</sup>) recorded at Phortse AWS, Camp II AWS, South Col AWS, Balcony AWS. Note that the lapse rate (LR) and saturated adiabatic lapse rate (SALR) are calculated between the Balcony (8430m) and South Col (7945m) AWSs.

	AWS Phortse (3810m)		AWS Camp II (6464m)		AWS South Col (7935m)		AWS Balcony (8430m)		LR (°Ckm <sup>-1</sup> )	SALR (°Ckm <sup>-1</sup> )
	$T$	$q$	$T$	$q$	$T$	$q$	$T$	$q$		
June	9.3	10.0	-4.6	3.4	-14.2	1.5	-18.9	1.4	-9.7	-7.9
July	10.2	11.5	-3.4	5.6	-11.5	3.3	-14.7	2.7	-6.6	-6.8
Monsoon	9.9	11.1	-4.1	5.2	-13.0	2.9	-16.0	2.6	-6.1	-7.0
October	5.0	6.9	-9.9	1.5	-21.4	0.9	-25.7	0.9	-9.1	-8.5

rise of 120%), whilst the increase in temperature ranges from 0.9degC at Phortse to 4.2degC at Balcony, with a signal that clearly increases with elevation (Table 1). The transition to the monsoon is also characterised by a reduction in mean wind speed, falling by 30–55% from June to July at the higher three stations (Figure 2).

The increase in specific humidity and temperature with the arrival of the monsoon coincides with a rise in relative humidity, most notable at the higher elevation stations, which join Phortse in being close to saturation (Figure 2). Evidence for more frequent cloud formation is also provided by changes in the lapse rate (LR, degCkm<sup>-1</sup>) calculated between neighbouring AWSs (subscripts 1 and 2):

$$LR = \frac{T_2 - T_1}{Z_2 - Z_1} \quad (1)$$

where  $T$  is the air temperature recorded at the respective AWS, which is at an altitude of  $Z$  meters above sea level.

Application of Equation (1) reveals that the LR shallows (temperatures fall less rapidly with altitude) when the monsoon arrives, and the largest change is observed for the LR between the South Col and Balcony AWSs (Figure 2 and Table 1). This results in the atmosphere becoming more aligned with a moist adiabat across the full 4.6km elevational range of the network, indicating latent heat release occurs at greater heights than seen in the pre- (June) and post-monsoon (October) (Figure 3). Temperatures even decline slightly less between the South Col and Balcony during this period than would be expected from the saturated adiabatic lapse rate (SALR; Figure 3 and Table 1). This suggests that either diabatic heating of ascending air by surface fluxes, or solar heating of the (non-ventilated) temperature sensor at the Balcony, where winds are relatively light (compared to the South Col) and the terrain is covered by highly reflective snow (Matthews *et al.*, 2020). Overall, the shift to shallower LR during monsoon supports conclusions from previous studies conducted at lower elevations in Nepal

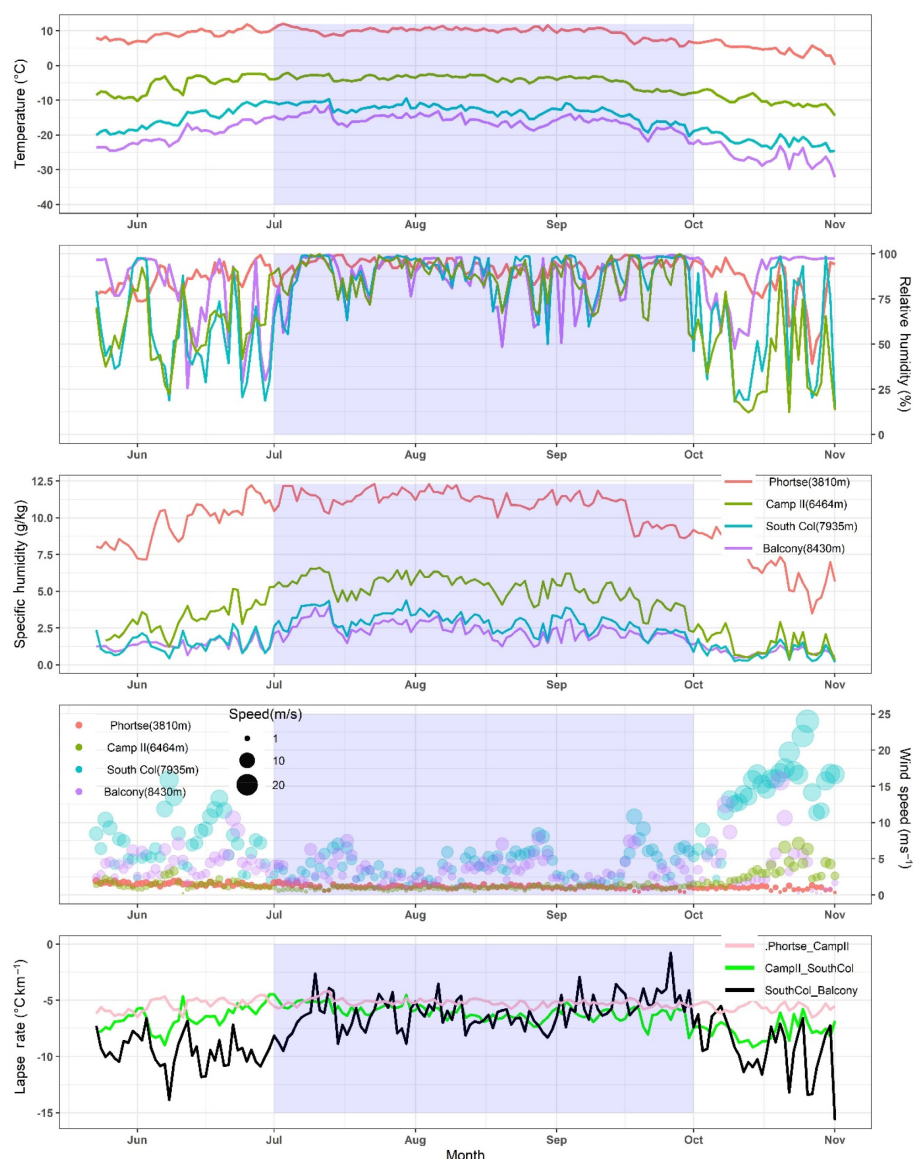


Figure 2. Mean daily temperature, relative humidity, specific humidity, wind speed and temperature LR between AWSs before, during (shaded) and after the monsoon. For wind speed, the size of the dot represents the strength of wind gust.

(Kattel *et al.*, 2013; Immerzeel *et al.*, 2014; Salerno *et al.*, 2015). It also explains why monsoon warming amplifies with height, analogous to the elevation-dependent warming anticipated in a warmer, more humid atmosphere under climate change (Pepin *et al.*, 2015).

From the above, we can extrapolate to make a conservative estimate of the mean air temperature at Mt Everest's unmonitored summit by taking the mean air temperature at the South Col during the monsoon (where winds are stronger and solar heating of the temperature sensor is less likely),



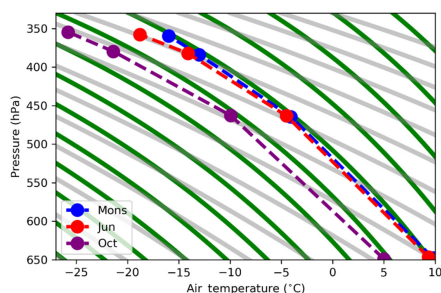


Figure 3. Mean air temperature and pressure recorded at the AWSs during the respective periods. The lines show moist adiabats (green) and dry adiabatic (grey) LRs.

and then integrating the SALR to 8849m. We assume that the SALR remains appropriate up to the summit because Perry *et al.* (2020) observed precipitation echo tops extending to almost 10 000m above sea level during a snowstorm on Mt Everest in May 2019.

The results from this analysis suggest a mean temperature at the summit of  $-19.1^{\circ}\text{C}$  during the monsoon. To place this seasonal 'warmth' in a more familiar alpine context, the United Kingdom's highest mountain would struggle to ever produce temperatures this low; the record of Hawkins *et al.* (2019) indicates that minimum temperature did not fall below  $-17.4^{\circ}\text{C}$  on the summit of Ben Nevis (1345m) during the period of direct observations (1883–1904). However, other popular trekking peaks in the mid-latitudes can produce cold temperatures comparable to Mt Everest's summit during the monsoon. For example, around 10% of monthly-mean January temperatures at the famous Mount Washington Observatory (1916m, New Hampshire, USA<sup>1</sup>) fell below  $-19.1^{\circ}\text{C}$  from the period of 1975 to 2004 (the most recent 30-year period archived at the KNMI climate explorer).<sup>2</sup> The high insolation found on the upper slopes of Mt Everest could also make it *feel* much warmer than indicated by the air temperature. Matthews *et al.* (2020) estimated that the snow surface at the summit may be warmed to  $0^{\circ}\text{C}$  under direct sunshine and light winds. Compared to the

snow surface, a mountaineer's less reflective down suit could be heated by the Sun even more effectively.

To summarise, the new weather observations from close to the summit of Mt Everest indicate that winds weaken and temperatures climb as the summer monsoon begins, due to a combination of warming at lower elevations and a shallowing of the LR. Should mountaineers make it past the deep snow and enhanced avalanche hazards of the lower slopes, they may encounter a monsoonal environment with cold hazards not dissimilar from the wintertime conditions found on much lower peaks climbed in the mid-latitudes, notwithstanding the much lower amounts of atmospheric oxygen at this extreme height. As new measurements become available, we hope to place the 2019 Mt Everest monsoon into a longer-term context. We are also exploring LR variability in the context of regional glacier–climate interactions.

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<sup>1</sup><http://www.mountwashington.org>

<sup>2</sup><http://climexp.knmi.nl>