DOI:
10.1175/BAMS-D-22-0120.1

Weather observations reach the summit of Mount Everest

Tom Matthews,[a] Baker Perry,[b] Arbindra Khadka,[c,d] Tenzing Gyalzen Sherpa,[e] Dibas Shrestha,[f] Deepak Aryal,[f] Subash Tuldahar,[g] Nirakar Thapa,[g] Niraj Pradhananga,[g] Peter Athans,[h] Dawa Yangzum Sherpa,[h] Heather Guy,[i] Anton Seimon,[b] Aurora Elmore,[j] Kristina Li,[k] Nicole Alexiev [k]

[a] *Department of Geography, King's College London, London, UK*

[b] *Department of Geography and Planning, Appalachian State University, Boone, North Carolina*

[c] *Univ. Grenoble Alpes, CNRS, IRD, Grenoble-INP, IGE, Grenoble, France*

[d] *International Centre for Integrated Mountain Development, Lalitpur, Nepal*

[e] *Shangri-La Nepal Trek PVT. LTD, Kathmandu, Nepal*

[f] *Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal*

[g] *Department of Hydrology and Meteorology, Government of Nepal, Kathmandu, Nepal*

[h] *The North Face, Alameda, California*

[i] *School of Earth and Environment, Leeds, University of Leeds, UK*

[j] *National Oceanic and Atmospheric Administration, Washington, D.C.*

[k] *National Geographic Society, Washington, D.C.*

Corresponding author: Tom Matthews, tom.matthews@kcl.ac.uk

ABSTRACT

The predictability of the weather on Mt. Everest's upper slopes can be a matter of life or death for those trying to climb the world's highest mountain, yet the performance of forecasts has been almost unknown due to a lack of surface observations. The extent to which climate change may be affecting this iconic location is also uncertain for the same reason. To address this data limitation, the National Geographic and Rolex Perpetual Planet Expedition installed the world's highest weather station network (reaching within 420 m of the summit) on the Nepal side of Mount Everest in 2019. Its observations have already generated considerable advances in understanding the meteorological environment on the mountain's upper slopes, but the network was compromised by damage to the highest stations in recent years. Here, we describe the expedition that upgraded the network and took it to new heights, focusing on the installation at the Bishop Rock (8,810 m), just below the summit. Almost 70 years after Everest was first climbed successfully, we can now provide open access data to illuminate conditions at Earth's highest climate frontier.

1. Introduction

Rising to 8,849 m a.s.l. (meters above sea level), the upper slopes of Mt. Everest experience barometric pressure around one-third of sea-level, strong winds, and air temperatures low enough to freeze exposed skin within a few minutes (Matthews et al., 2020a; Moore and Semple, 2011). Such conditions mean that margins of safety are often fine and deterioration in the weather can have severe consequences. Indeed, it is estimated that bad weather contributes to 25 % of the deaths on the mountain (Firth et al., 2008), including perhaps the infamous disappearance of Mallory and Irvine (Moore et al., 2010) and during the deadly 1996 "into thin air" disaster (Moore and Semple, 2006). Whilst the extreme nature of Mt. Everest's weather is well known anecdotally, detailed scientific understanding of its climate has been lacking due to few weather observations gathered from the highest reaches of the mountain (Matthews et al., 2020b). Beyond mountaineering safety, the limited understanding of the current conditions or climatological trends translates to large uncertainty in the consequences of climate change for this critical "water tower", so called because of its importance as a water source to help sustain downstream demand (Immerzeel et al., 2019).

To both improve climber safety and enhance understanding of water resources, an international team of scientists and Sherpa installed the world's highest weather station network on the southern flanks of Mt. Everest during the 2019 National Geographic and Rolex Perpetual Planet Expedition, as detailed in Matthews et al. (2020b). With five stations between 3,840 m a.s.l. (Phortse) and 8,430 m a.s.l. (the 'Balcony'), this network has already generated numerous discoveries, including the identification of remarkable day-to-day variability in oxygen availability that underlines the importance of a well-selected summit window for climbers (Matthews et al., 2020a); and revealing the very high levels of insolation on the upper slopes – enough to drive surface melting at air temperatures well below 0°C (Matthews et al., 2020b) and resulting in an extreme sensitivity to surface albedo (Potocki et al., 2022). Additionally, the network has helped quantify gradients in air temperature and humidity (Khadka et al., 2021), whilst the use of air mass tracking techniques alongside precipitation observations from the lower stations have provided insights to the provenance of precipitation nourishing the Khumbu Glacier (Perry et al., 2020). Both contributions enhance understanding of regional glacier sensitivity to climate change, which in turn is relevant for quantifying potential future freshwater availability.

2. Reaching new heights

The 8,430 m a.s.l. Balcony was not originally intended to be the site of the highest station. Instead, this choice reflected the severely limited options for acceptable locations (stations require relatively flat areas, near the standard climbing route but not in the way of climbers, and anchored into bedrock, which is often covered by snow and ice) as well as the logistical challenges of a very congested summit night in 2019 (Matthews et al., 2020b). Tantalizing questions remained from leaving the upper ~420 m unmonitored: what is the mass balance of the summit snowcap and how might this (and the height of Mt. Everest) change as the climate warms? How well are the critical summit-ridge winds captured by weather forecasts? With the demise of the Balcony weather station in January 2020, the upper ~900 m of Mt. Everest was once again unmonitored. Wind measurements from the second highest (South Col; 7,945 m a.s.l) weather station ceased around the same time. Therefore, a decision was made to undertake a maintenance expedition to repair the latter and *replace* the former, ideally at an even higher site, in an effort to help resolve these unanswered questions about the weather near the summit.

The *Return to Everest* expedition was launched in partnership with the Department of Hydrology and Meteorology (Government of Nepal); Department of National Parks and Wildlife Conservation (Government of Nepal); and Tribhuvan University in April 2022, following two years of delay due to the Covid-19 global pandemic. During the expedition, we learned that a Chinese expedition was installing weather stations on the north side of the mountain, reaching very close to the summit, at a height of either 8,800 m a.s.l. (Gui, 2022) or 8,830 m a.s.l. (India Today, 2022), depending on reports. We congratulate them on this remarkable accomplishment and highlight that simultaneous observations from altitudinal transects on either side of the mountain may offer rich insights into mountain meteorology. The Chinese team installed stations based on our 2019 design (Matthews et al., 2020b), whereas we updated the choice of wind sensors because of the high failure rate for the model deployed at the South Col and Balcony in 2019, with all (four) being destroyed by strong winds during their first winter. Our new design for the 2022 expedition featured three *different* sensors for redundancy: a special polycarbonate R.M. Young 05108 Alpine anemometer; a Richards C5C stainless steel three-cup anemometer; and an experimental pitot tube built by the Mount Washington Observatory. These were added to the South Col weather station (Fig. 1), and to the system intended as a replacement for the Balcony station. Note that the continuity of wind observations from the three lower stations mean that there was no need to make similar replacements at these other sites. Below we focus on the efforts to replace the Balcony weather station.

Arriving in Everest Base Camp (5,300 m a.s.l) on 13 April 2022, our team prepared in the usual way for a summit attempt, completing one rotation through the higher camps in between rest periods. The Camp 2 weather station (6,464 m a.s.l) was also inspected during this acclimatization effort and found to be in good working order, requiring only the net-radiometer to be re-levelled. In an effort to guard against being caught in another crowded summit night, the team was ready for the summit push by 14 May, which was well ahead of other teams.. An anxious wait followed in Base Camp as we delayed leaving until the rope-fixing team had closed in on the summit. However, with favorable news of the latter's progress accompanied by a weather forecast indicating light winds (Fig. 2a), we left Basecamp on 6 May aiming to push for the summit on 10 May.

On our first rest day at Camp 2 (7 May), updates from our forecasting team (co-authors Guy and Seimon) gave slight cause for alarm. Winds on 10 May were now forecast to be stronger than previously thought (Fig. 2b). However, the shift was *only* from very favorable to marginal, and combined with news that the ropes were unlikely to be in position by May 9, we decided to continue resting and target 10 May. Everything changed, though, on 8 May. That morning's forecast predicted winds could peak at around 24 m s^{-1} on 10 May (Fig. 2c)–

conditions that the leadership team agreed would not be suitable for the climb and installation. With supplies at Camp 2 running low, we decided to leave immediately in an attempt to make the 9 May weather window before it closed. These circumstances were not ideal. The ascent would now require a rapid ~1,500 m climb straight to Camp 4 (the South Col, 7,945 m a.s.l), where there would be very little time to recover before leaving for the summit. The team pushed hard to arrive by 20:00 NPT (Nepal Standard Time) 8 May, enabling just a few hours rest before departing again at ~01:00 NPT 9 May.

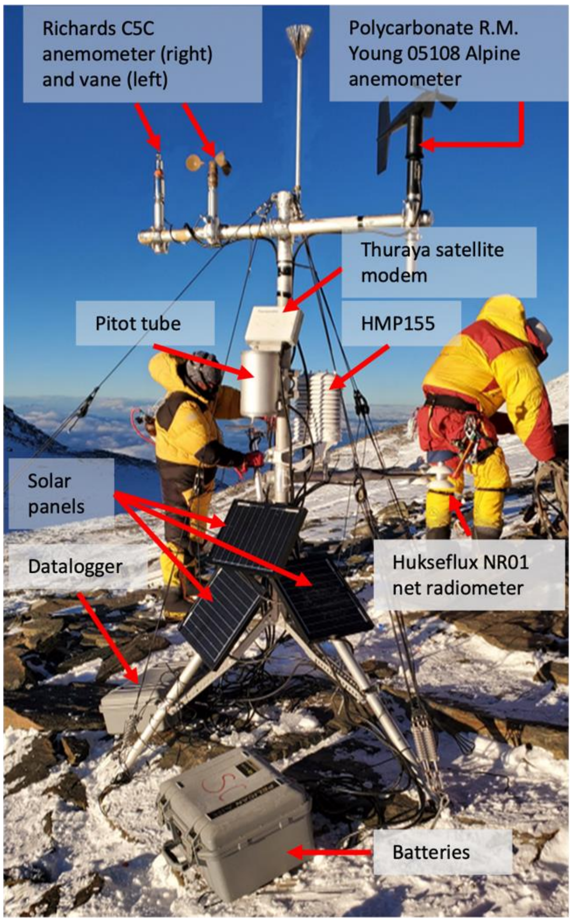

Fig. 1. Tenzing Gyalzen Sherpa (right) and Mingma Nuru Sherpa (left) work on upgrading the South Col automatic weather station at 7,945 m a.s.l. In addition to the wind sensors mentioned in the text, note that the HMP155 measures temperature and relative humidity; and the Hukseflux net radiometer measures incoming and outgoing short- and long-wave radiation. A (Vaisala PTB210) barometer is also located in the datalogger enclosure. All data are sent in near real-time via the Thuraya satellite modem, with up to 13 transmissions per day. See Matthews et al. (2020b) for further details of the station design.

The ascent from Camp 4 proceeded well with 13 Sherpa leading scientists Khadka and Matthews as they made good time climbing, despite carrying an extra 60 kg in unassembled parts for the replacement high station. However, upon rounding the South Summit (8,749 m a.s.l.) to gain the exposed summit ridge, it became clear that winds were stronger than the forecast guidance. Nevertheless, at ~09:00 NPT the team reached the target site (Bishop Rock: 8,810 m a.s.l, surveyed at this height by co-author Athans during a 1999 National Geographic survey) and the elite Sherpa team led by Tenzing Gyalzen pursued the installation despite the very difficult circumstances brought on by the weather conditions and physical fatigue. Their success (Fig. 3) was built upon years of training in high-altitude mountaineering and for some of the team, experience of working with the network since its installation in 2019. The first observations from this summit station indicate that the wind-chill temperature must have been close to -40°C (with a corresponding facial frostbite time of less than ten minutes) whilst the station was being installed (Fig. 4). These conditions were endured for almost three hours (the installation was completed at ~12:00 NPT), yet the only (minor) frostbite sustained was to the fingers of scientist Matthews, whose hands were covered far more than those of the Sherpa performing the vast majority of the installation. The Sherpa indeed demonstrated a remarkable ability to perform fine dexterous work without gloves, despite prolonged exposure to the significant cold hazard.

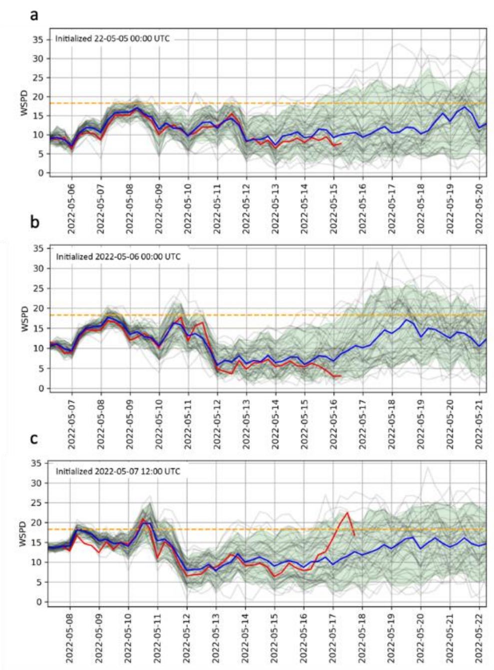

Fig.2. The original European Centre for Medium Range Weather Forecasting (ECMWF) forecast plots used on the mountain (received via WhatsApp by the basecamp team). All forecasts were interpolated from pressure levels to the latitude, longitude and height of Mt. Everest’s summit. Initialization dates for the forecast runs are annotated top left of each panel. Note that green shading spans 5th-95th percentiles of the ensemble; blue is the ensemble mean;

and red is the deterministic forecast. The orange dashed line was the authors' best estimate of a safe climbing threshold. Note that the units of all wind speeds are m s^{-1}.

Fig. 3. Lead Sherpa (Sirdar) Tenzing Gyalzen (right) and Kami Temba Sherpa (left) put the finishing touches to the Bishop Rock weather station (8,810 m a.s.l). View is to the southwest, with the peak of Mt. Lhotse (8,516 m a.s.l.) visible in the background.

After safely returning to Camp 4 (~14:00 NPT), most of the team continued to maintain the nearby South Col weather station, completing the upgrade by ~18:30 NPT. Both stations were therefore operational to record the hurricane-force gusts (reaching 36 m s^{-1} at the Bishop Rock) when the winds strengthened as forecast on 10 May (Fig. 4). This acceleration was consistent with a steepening of the upper-troposphere pressure gradient in the vicinity of Mt. Everest, which was likely driven in part by warm air advection on the eastern flank of cyclone Asani (Fig. 5). The strong winds presented some difficulty for our safe exit from Camp 4 during the morning, but all were able to descend without incident. Meanwhile at the summit, facial frostbite time fell to less than two minutes as the wind chill plunged to almost -50°C (Fig. 4).

Such a severe cold hazard during the main spring climbing season highlights the importance of a well-chosen summit window. However, the surprisingly strong winds encountered earlier by our team when installing the Bishop Rock station on 9 May underscores that there is still considerable potential to improve weather forecasts on the mountain (Matthews et al., 2020b). Fortunately, the forecasts from the European Centre for Medium Range Weather Forecasting we used *did* predict the generally favorable weather window on 12 May (Fig. 4), during which the first all-Black ("Full Circle") team to climb Mt. Everest made their successful and historic summit attempt. Since our teams were adjacent in Base Camp and shared several personal and professional connections, we collaborated closely and were honored to share this forecast to help identify the timing of the summit push.

Beyond these insights relevant to mountaineering safety, initial observations from Bishop Rock indicate conditions very conducive to sublimation. Insolation reaching close to 1200 W m^{-2} and relative humidity falling below 2 % (Fig. 4) may drive very steep near-surface gradients in vapor pressure as the surface is radiatively heated relative to an atmosphere so far from saturation. The strong winds observed (Fig. 4) would also work to amplify sublimation by enhancing turbulent mixing. We therefore expect that sublimation rates are comparable to those at the South Col, if not higher (Potocki et al., 2022). With this relatively high mass turnover, appreciable interannual variability (possibly exceeding 100 mm) may be possible in the thickness of the summit snowpack and therefore the height of Mt. Everest. We will model the energy and mass fluxes – including estimating longer-term trends in snowpack temperature and melt occurrence (Matthews et al., 2020b) – as more data become available.

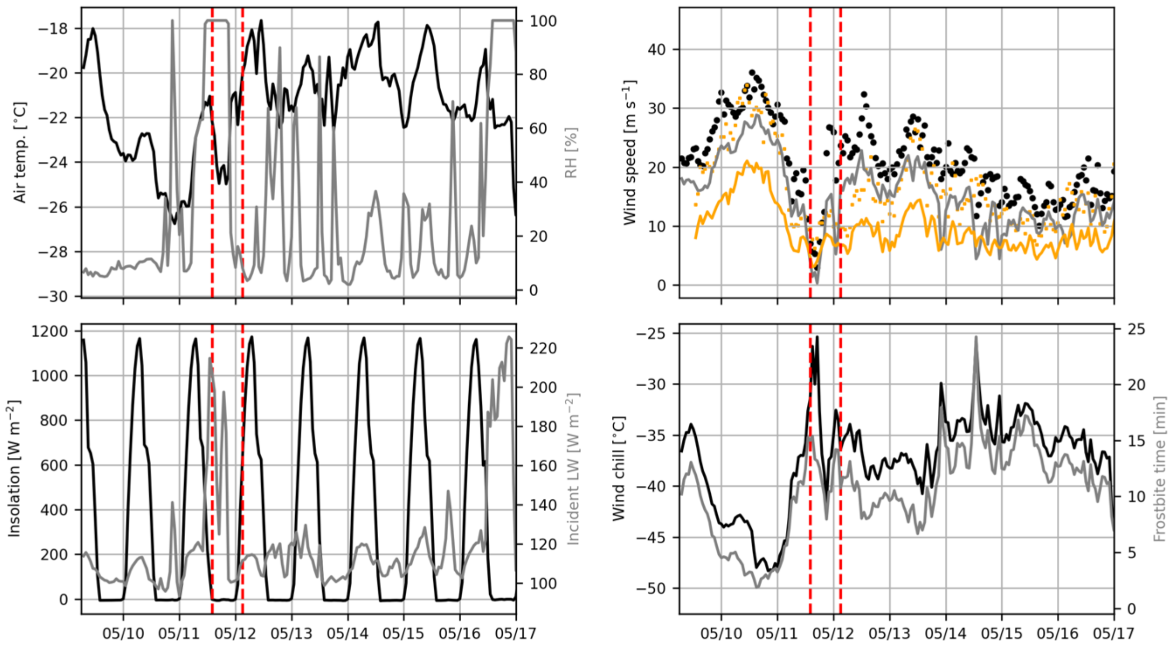

Fig. 4. The first week of observations from the Bishop Rock weather station (8,810 m a.s.l.). (a) air temperature (black) and relative humidity (RH; gray); (b) hourly mean wind speed (gray), maximum (three-second) gust (black circles), and South Col station (7,945 m a.s.l.) average winds (orange lines) and maximum gusts (orange circles); (c) incident shortwave radiation (insolation; black) and incident longwave radiation (LW; gray); (d) wind chill temperature (black) and facial frostbite time (gray). The dashed red lines demarcate the approximate time that the Full Circle team summited Mt. Everest. Note that all dates are UTC.

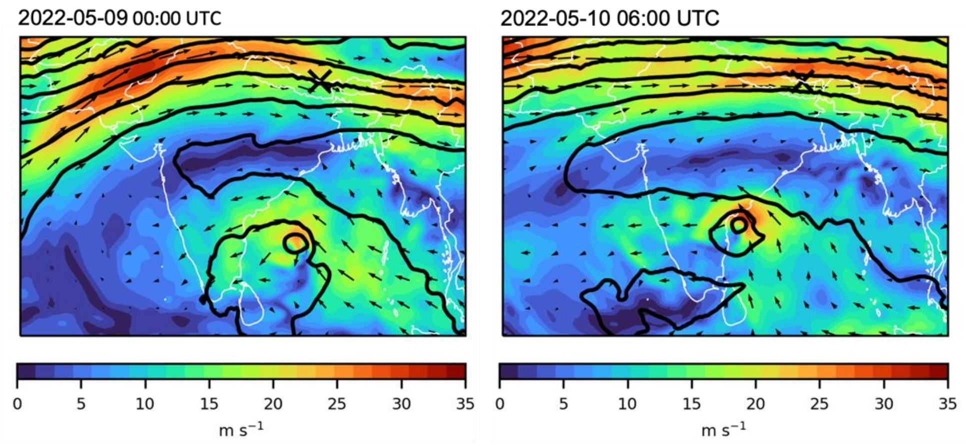

Fig. 5. Wind speeds (shading) and geopotential height (black lines) on the 300 hPa surface from the European Centre for Medium Range Weather Forecasting ERA5 dataset for 00:00 UTC on 09 May (left) and 06:00 UTC on 10 May (right). Wind direction and magnitude is also indicated by the vectors. Note that the position of Mt. Everest is marked by the black cross, and the cyclonic feature off the southeast coast of India is cyclone Asani.

Other researchers are also strongly encouraged to make the most of these data in studying an environment that has, for almost 70 years since the first summit (in 1953), been a site of global significance, yet unmonitored due to profound logistical challenges. That these difficulties were overcome speaks to the remarkable ability of the climbing Sherpa who made it possible (see *Acknowledgments*). To maximize its utility, data from the Bishop Rock station are freely available to the public, distributed as both a (lightly) quality-controlled archive, and via a low bandwidth page that should be accessible even for mountaineers experiencing patchy internet connectivity at Mt. Everest Base Camp (see *Data Availability Statement*). We hope that opening access to the data in these ways will help make climbing Mt. Everest safer, and will accelerate scientific understanding of this high-altitude climate frontier in the heart of the Himalayan water tower.

Acknowledgments.

This research was conducted in partnership with National Geographic Society, Rolex, Tribhuvan University, the Department of Hydrology and Meteorology (Government of Nepal), and the Department of National Parks and Wildlife Conservation (Government of Nepal). We thank Shangri-La Nepal Trek for their unwavering logistical support, and we acknowledge the Mount Washington Observatory for their invaluable help designing the pitot tube; AR Richards is thanked for the stainless-steel anemometer deployed on the South Col and Bishop Rock weather stations. We are also grateful to the European Centre for Medium Range Weather Forecasting for providing access to their real-time forecast products.

Weather station installation team

The station was installed by an elite Sherpa team to whom we – and the high-altitude meteorological community – will always be indebted. The team members were: Tenzing Gyalzen Sherpa (Sirdar/Lead), Phu Tashi Sherpa, Lhakpa Tsering Sherpa, Ila Nuru Sherpa, Kami Temba Sherpa, Lhakpa Nuru Sherpa, Ngima Nurbu Sherpa, Nima Cherri Sherpa, Nima Kancha Sherpa, Pasang Kami Sherpa, Kancha Nuru Sherpa, Ngima Namgyal Sherpa, and Mingma Nuru Sherpa.

Data Availability Statement.

The archive of (lightly) quality-controlled data is available at: https://www.nationalgeographic.org/projects/perpetual-planet/everest/weather-data/, and the most recent data can be viewed at the low-bandwidth page: https://everest-pwa.nationalgeographic.org

REFERENCES

Firth, P.G., Zheng, H., Windsor, J.S., Sutherland, A.I., Imray, C.H., Moore, G.W.K., Semple, J.L., Roach, R.C., Salisbury, R.A., 2008. Mortality on Mount Everest, 1921-2006: descriptive study. BMJ 337, a2654. https://doi.org/10.1136/bmj.a2654

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B.J., Elmore, A.C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J.S., Koppes, M., Kraaijenbrink, P.D.A., Kulkarni, A.V., Mayewski, P., Nepal, S., Pacheco, P., Painter, T.H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A.B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., Baillie, J.E.M., 2019. Importance and vulnerability of the world's water towers. Nature 1–1. https://doi.org/10.1038/s41586-019-1822-y

India Today. China sets up the world's highest weather station on Mt. Everest. Available at: Accessed 15/05/2022, https://www.indiatoday.in/science/story/china-sets-up-world-s-highest-weather-station-on-mount-everest-1945359-2022-05-04.

Khadka, A., Matthews, T., Perry, L.B., Koch, I., Wagnon, P., Shrestha, D., Sherpa, T.C., Aryal, D., Tait, A., Sherpa, T.G., Tuladhar, S., Baidya, S.K., Elvin, S., Elmore, A.C., Gajurel, A., Mayewski, P.A., 2021. Weather on Mount Everest during the 2019 summer monsoon. Weather 76, 205–207. https://doi.org/10.1002/wea.3931

Matthews, Tom, Perry, L.B., Lane, T.P., Elmore, A.C., Khadka, A., Aryal, D., Shrestha, D., Tuladhar, S., Baidya, S.K., Gajurel, A., Potocki, M., Mayewski, P.A., 2020a. Into

Thick(er) Air? Oxygen Availability at Humans' Physiological Frontier on Mount Everest. iScience 23. https://doi.org/10.1016/j.isci.2020.101718

Matthews, T., Perry, L.B., Koch, I., Aryal, D., Khadka, A., Shrestha, D., Abernathy, K., Elmore, A.C., Seimon, A., Tait, A., Elvin, S., Tuladhar, S., Baidya, S.K., Potocki, M., Birkel, S.D., Kang, S., Sherpa, T.C., Gajurel, A., Mayewski, P.A., 2020b. Going to Extremes: Installing the World's Highest Weather Stations on Mount Everest. Bull. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-19-0198.1

Matthews, Tom, Perry, L.B., Lane, T.P., Elmore, A.C., Khadka, A., Aryal, D., Shrestha, D., Tuladhar, S., Baidya, S.K., Gajurel, A., Potocki, M., Mayewski, P.A., 2020b. Into Thick(er) Air? Oxygen Availability at Humans' Physiological Frontier on Mount Everest. iScience 23. https://doi.org/10.1016/j.isci.2020.101718

Moore, G.W.K., Semple, J.L., 2011. Freezing and Frostbite on Mount Everest: New Insights into Wind Chill and Freezing Times at Extreme Altitude. High Alt. Med. Biol. 12, 271–275. https://doi.org/10.1089/ham.2011.0008

Moore, G.W.K., Semple, J.L., 2006. Weather And Death On Mount Everest: An Analysis Of The Into Thin Air Storm. Bull. Am. Meteorol. Soc. 87, 465–480. https://doi.org/10.1175/BAMS-87-4-465

Moore, G.W.K., Semple, J.L., Sikka, D.R., 2010. Mallory and Irvine on Mount Everest: Did extreme weather play a role in their disappearance? Weather 65, 215–218. https://doi.org/10.1002/wea.590

Perry, L.B. *et al.* (2020) 'Precipitation Characteristics and Moisture Source Regions on Mt. Everest in the Khumbu, Nepal', *One Earth*, 3(5), pp. 594–607. doi:10.1016/j.oneear.2020.10.011.

Potocki, M., Mayewski, P.A., Matthews, T., Perry, L.B., Schwikowski, M., Tait, A.M., Korotkikh, E., Clifford, H., Kang, S., Sherpa, T.C., Singh, P.K., Koch, I., Birkel, S., 2022. Mt. Everest's highest glacier is a sentinel for accelerating ice loss. Npj Clim. Atmospheric Sci. 5, 1–8. https://doi.org/10.1038/s41612-022-00230-0

Rui, G., 2022: Chinese researchers set up world's highest weather station on Mount Everest to study roof of the world. South China Post. Accessed 16/05/2022, https://www.scmp.com/news/china/science/article/3176469/chinese-researchers-set-worlds-highest-weather-station-mount