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Automatic weather station observations of the April 2014 Mount Everest avalanche

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ABSTRACT

Instrumental records indicate a warming of approximately 0.8 °C has occurred in the Mount Everest region since the 1980s, which has resulted in a 100–300 m rise in the height at which the ground is permanently frozen as well as a retreat and thinning of Everest's glaciers. For some time, there have been concerns that this warming and the resultant changes in the region's glaciers may be increasing the risks for travellers to Mount Everest as well as the indigenous populations who support them. On 18 April 2014, an avalanche caused by the collapse of a large serac swept down Mount Everest's Khumbu Ice Fall resulting in the deaths of 16 Sherpa. Although satellite imagery has been used to estimate the size of the serac, in situ data on the avalanche itself has not been available. Here we show that this event coincided with an approximate 15-min-long wind, thermal, and moisture anomaly, which was observed at the Nepal Climate Observatory-Pyramid situated 10 km from Mount Everest. We argue that this anomaly was associated with the avalanche and thereby provides some information on its scale and duration as well as a potential mechanism to monitor future events in this remote and data-sparse region.

Introduction

Instrumental records indicate a warming of approximately 0.8 °C has occurred in the Everest region since the 1980s (Diodato et al., 2012; Salerno et al., 2014), which has resulted in a 100–300 m rise in the height at which the ground is permanently frozen in the region (Fukui et al., 2007) as well as a retreat and thinning of the region's glaciers (Bolch et al., 2008; Thakuri et al., 2014). This period of warming has coincided with the Everest region becoming an increasingly important destination for both climbers and trekkers (Nyaupane and Chhetri, 2009). For some time, there have been concerns that this warming and the resultant changes in the region's glaciers may be increasing the risks for the large number of travelers to the Mount Everest region as well as the indigenous populations who support them (Law and Rodway, 2008; Nyaupane and Chhetri, 2009; Scott et al., 2012; Krakauer, 2014).

From the Nepalese or south side of Mount Everest, the principal climbing route extends from Everest Base Camp up through the Khumbu Ice Fall and into the Western Cwm, named by George Mallory in 1921, and then onto the summit (Figs. 1 and 2). The Western Cwm and indeed the upper Khumbu Valley are surrounded by steep mountainsides containing hanging glaciers, glaciers that are frozen onto the steep sides of valleys, which provide approximately 75% of the annual mass accumulation of the valley glacier (Inoue, 1977). As such, avalanches originating on these hanging gla-

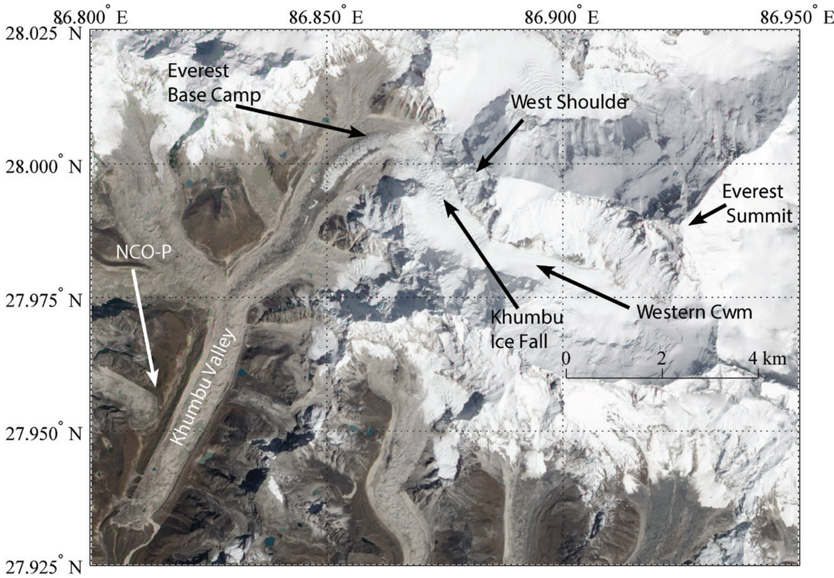

FIGURE 1. Advanced Land Imager (EO-ALI) true color satellite image of the Mount Everest region taken on 4 October 2010. Places of interest are indicated. (Image courtesy of NASA)

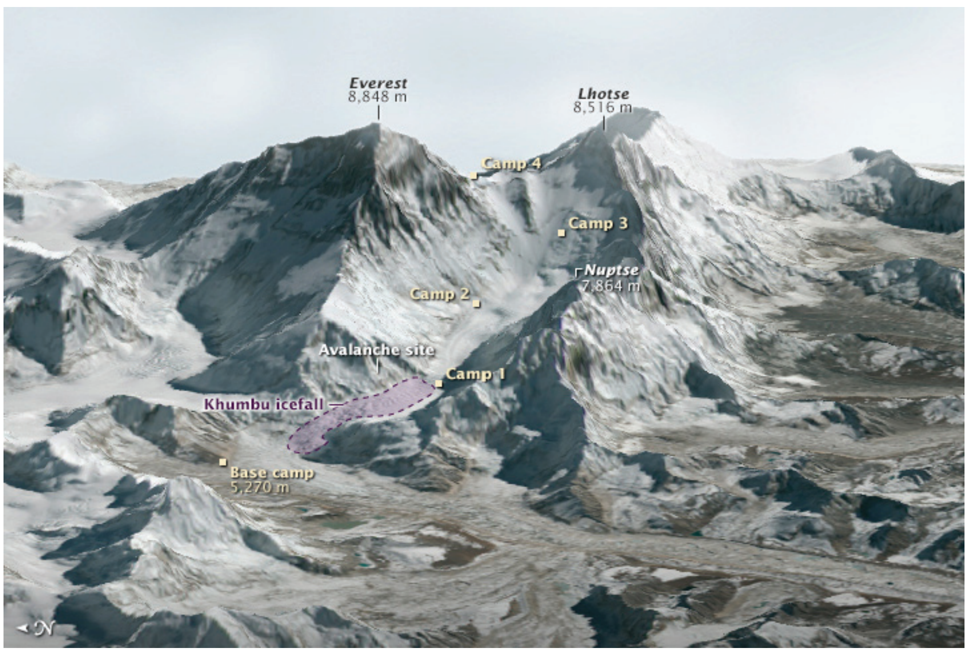

FIGURE 2. Three-dimensional rendering of the Mount Everest region based on data collected by the Advanced Land Imager (EO-ALI) on the Landsat 8 satellite and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the Terra satellite showing the approximate location of the April 2014 Avalanche. (Image courtesy of NASA)

ciers play an important role in the mass balance of the Khumbu Glacier and are a common occurrence in the region (Benn et al., 2012; McClung, 2016).

These so-called glacier avalanches are a class of catastrophic mass flow that occurs in glaciated environments (Röthlisberger, 1977; Evans and Delaney, 2015). Such events may occur as a part of a cycle whereby a hanging glacier, under constant climatic conditions, must release ice in order to maintain its equilibrium size (Pralong and Funk, 2006) or as an adjustment process as the glacier responds to a warming climate (Deline et al., 2015). As a result of the large amount of potential energy stored in a hanging glacier, a glacier avalanche can have significant impacts on its environment (Deline et al., 2015). The impacts include the triggering of high-speed powder snow avalanches, a type of gravity current characterized by a dense core of snow and ice with a lighter plume or cloud of snow or ice crystals suspended in whole or in part by turbulent air motion (Hopfinger and Tachon-Danguy, 1977; Sovilla et al., 2015; Bartelt et al., 2016). It is possible for this suspension or plume to decouple from the denser core resulting in a so-called air blast or avalanche wind that can propagate long distances downstream (Grigorian, 1975; Hopfinger and Tachon-Danguy, 1977; Röthlisberger, 1977; Bartelt et al., 2016).

Although mass balance estimates suggest that avalanches are common in the region, there are few if any

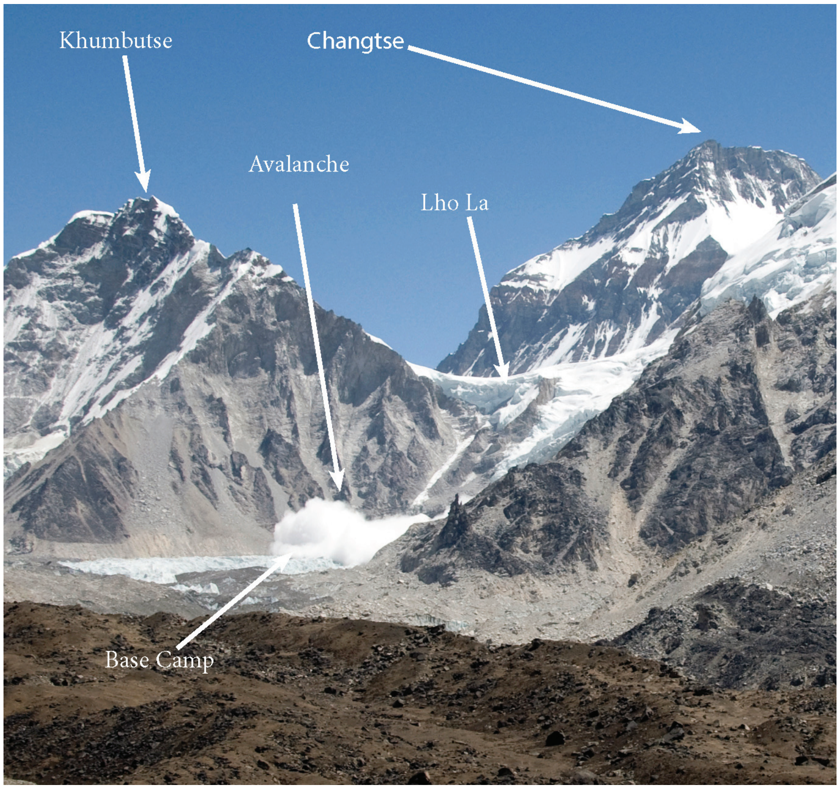

FIGURE 3. An avalanche impacting the Mount Everest Base Camp region on 9 May 2007. The Khumbu Ice Fall is situated behind the ridge in the foreground. Changtse (7543 m a.s.l.) and Khumbtse (6636 m a.s.l.), the mountains situated to the immediate north and west of Mount Everest are indicated as is the Lho La (6006 m a.s.l.), the pass between the West Ridge of Mount Everest and Khumbtse. The photograph was taken along the west ridge of the Khumbu Valley close to the site of the Nepal Climate Observatory-Pyramid (NCO-P). (Photograph courtesy of G. W. K. Moore)

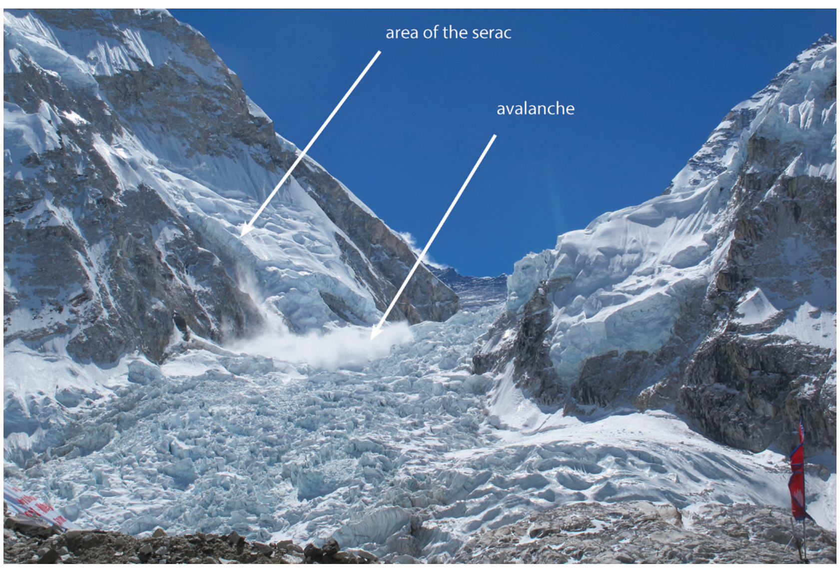

FIGURE 4. The Khumbu Ice Fall from the Mount Everest Base Camp on 8 April 2014 at 11:28 Nepal Standard Time. At this time, a small precursor avalanche (indicated by the arrow) was taking place. The origin of this avalanche was in the vicinity of the serac (indicated by the arrow) that is believed to have caused the large avalanche 10 days later on 18 April 2014. At its narrowest point, the Ice Fall is approximately 700 m wide. (Photograph courtesy of S. Stokes)

records of these events (McClung, 2016). Figure 3 shows a powder snow avalanche that originated along a hanging glacier above the Khumbu Ice Fall and subsequently engulfed Everest Base Camp on 7 May 2009 resulting in the deaths of 3 Sherpa who were in the Ice Fall at the time.

Based on first-person accounts, the 18 April 2014 event was caused by the collapse of a serac that was associated with a hanging glacier along the west shoulder of Mount Everest (Barry and Bowley, 2014; Narula, 2014). Ten days earlier on 8 April 2014, a small precursor avalanche occurred as a result of instability of the same hanging glacier (Stokes et al., 2015). A photograph of this event is shown in Figure 4.

The timing of the event on 18 April is uncertain, with the New York *Times* reporting that it occurred around 6:30 a.m. local time (Barry and Bowley, 2014). In contrast, the BBC stated that it occurred approximately 15 min later (BBC, 2014). Jon Krakauer (2014), writing in the *New Yorker*, stated that it occurred "before 7:00 local time." It is likely that all times quoted in news reports of the event were obtained secondhand through inter-

FIGURE 5. The Khumbu Ice Fall from the Mount Everest Base Camp on 18 April 2014 showing the avalanche moving down through the Ice Fall. At its narrowest point, the Ice Fall is approximately 700 m wide. (Photograph courtesy of Mark Horrell)

views with persons at Base Camp and therefore subject to some uncertainty that was compounded by the chaotic environment associated with the rescue efforts that occurred in the aftermath of the event (Wallace, 2014; Stokes et al., 2015). Perhaps the most definitive first-person account as to the timing of the event comes from Wallace (2014). She was a doctor at Base Camp and notes being awoken by a loud rumble and then falling back asleep before being awoken again around 6:45 a.m. by the base-camp manager to assist in the treatment of victims. Please note that all times in this paper are with respect to Nepal Standard Time, 5 hours and 45 minutes ahead of Greenwich Mean Time.

Other details regarding the avalanche are better known. On the morning of the 18 April, more than 30 Sherpa were in the Ice Fall assisting in the supply of the high camps on the mountain (Wallace, 2014; Stokes et al., 2015). Many in the Ice Fall at this time were the highly skilled "Ice Fall Doctors" who maintain this dangerous route for the benefit of the climbing parties (Wallace, 2014). Of these, 16 were killed and 9 injured in the ensuing avalanche, making this one of the deadliest days in Everest's climbing history (Narula, 2014).

A subsequent analysis of high-resolution satellite imagery from DigitalGlobe and Spot taken before and after the event indicated that the serac that collapsed, giving rise to the avalanche, had a surface area of 500 m^2 and a thickness of 35 m and fell from an initial height of 6200 m a.s.l. to the Ice Fall 300 m below[1] (McMillan, 2014). The volume of the ice that triggered the avalanche was therefore estimated to be 20,000 m^3 and, assuming a density of 900 kg m^{-3}, it had a mass of 1.6×10^7 kg. The deaths occurred in a region that extended 200 m vertically below the impact point of the serac (Wallace, 2014). Assuming that the mass of ice tumbled down through this disaster area, it fell a total distance of 500 m and so the avalanche released 8×10^{10} Joules of energy—an amount equivalent to 20 metric tons of TNT.

The extent of the avalanche can be seen in the photograph shown in Figure 5. A large plume of what appears to be snow and/or ice crystals can be seen to span the 700 m width of the Ice Fall. Based on the height of the features in the photograph, the plume appears to have been 100 m high. It can be seen to extend downwards a distance of 500 m from the Ice Fall toward Everest Base Camp, where the photograph was taken. Based on this photograph, the plume had a volume of 350,000 m^3.

Observations

The Nepal Climate Observatory-Pyramid (NCO-P), a World Meteorological Organization Global Atmosphere Watch station, is situated at a height of 5079 m a.s.l., approximately 10 km down the Khumbu Valley from Mount Everest (Fig. 1) with an exposure that faces the mountain (Fig. 3). An automatic weather station (AWS) situated on a ridge approximately 140 m above the valley floor has been collecting meteorological data, including wind speed and direction, humidity, and temperature since 2006 (Bonasoni et al., 2008, 2010). At this location, the Khumbu Valley is approximately 2 km wide with steep sides with maximum heights above the valley floor that exceed 700 m (Fig. 6).

[1] All values relating to the characteristics of the avalanche are approximate.

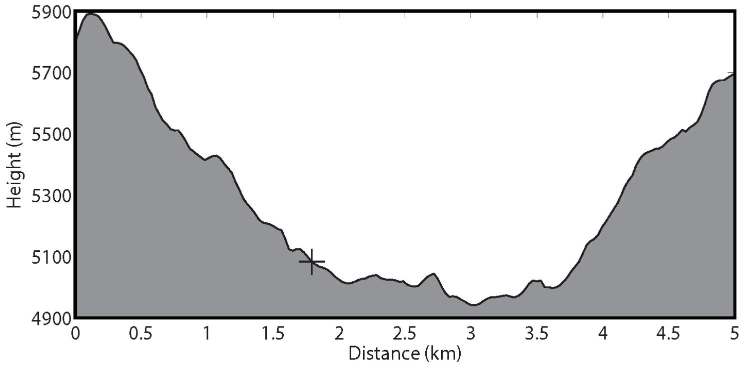

FIGURE 6. Cross section of the height of the Khumbu Valley in the vicinity of the NCO-P based on the ASTER v2 digital elevation model (30 m resolution). The location of the weather station is indicated by the '+'.

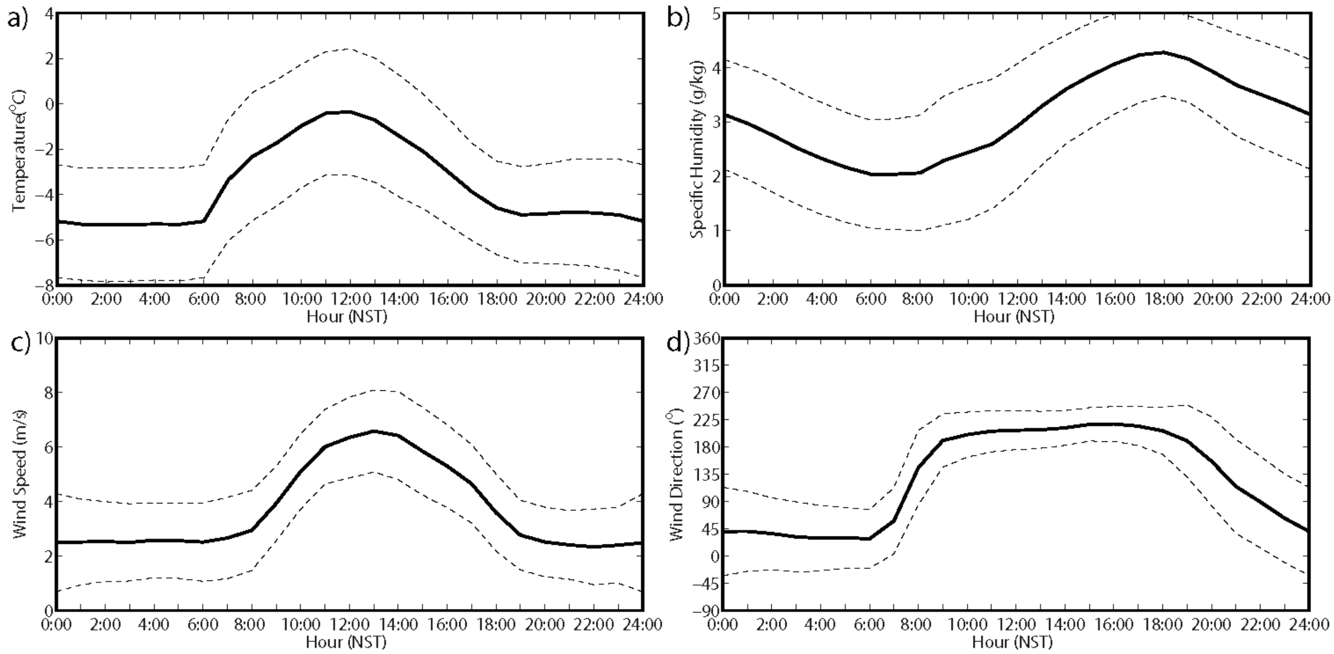

FIGURE 7. The climatological daily cycle of (a) temperature (°C), (b) specific humidity (g kg^{-1}), (c) wind speed (m s^{-1}), and (d) wind direction (°) at the NCO-P from 0:00 to 24:00 Nepal Standard Time. The mean values are given by the solid lines; the dashed lines represent 1 standard deviation above and below the respective mean. The time series are derived from observations from 1–30 April during 2006–2014.

Figure 7 shows the climatological daily cycle in temperature, specific humidity, wind speed, and wind direction at the NCO-P based on data collected during April 2006–2014. As can be seen from this figure, the meteorology of the region is dominated by the diurnal cycle of solar heating. The temperature undergoes a daily cycle with values near –4 °C during the night and close to 0 °C during the day. During April, the warming abruptly begins at sunrise around 6:00 a.m. and ends at sunset around 7:00 p.m. The specific humidity has a daily cycle that is phase shifted by approximately 6 hours with respect to that for the temperature. This phase shift is likely associated with sublimation and evaporation from the nearby glaciers that would tend to be largest when the surface is warmest later in the day. Wind speeds are low during the night and undergo an increase in the morning that is associated with a change in wind direction from downvalley, that is, wind direction near 0°, to upvalley, that is, wind direction near 180° (Bonasoni et al., 2008). A corresponding reduction in wind speed with a reversal in wind direction occurs during the evening. It is most likely that this behavior is associated with the valley winds that transport air down the valley during the nighttime and air up the valley during the daytime (Barry, 2008).

Figure 8 shows time series of temperature, specific humidity, wind speed, and wind direction from the NCO-P, recorded every minute, from 5:00 a.m. to 8:00 a.m. on 18 April 2014. Consistent with the climatology shown in Figure 7, the warming on 18 April began just

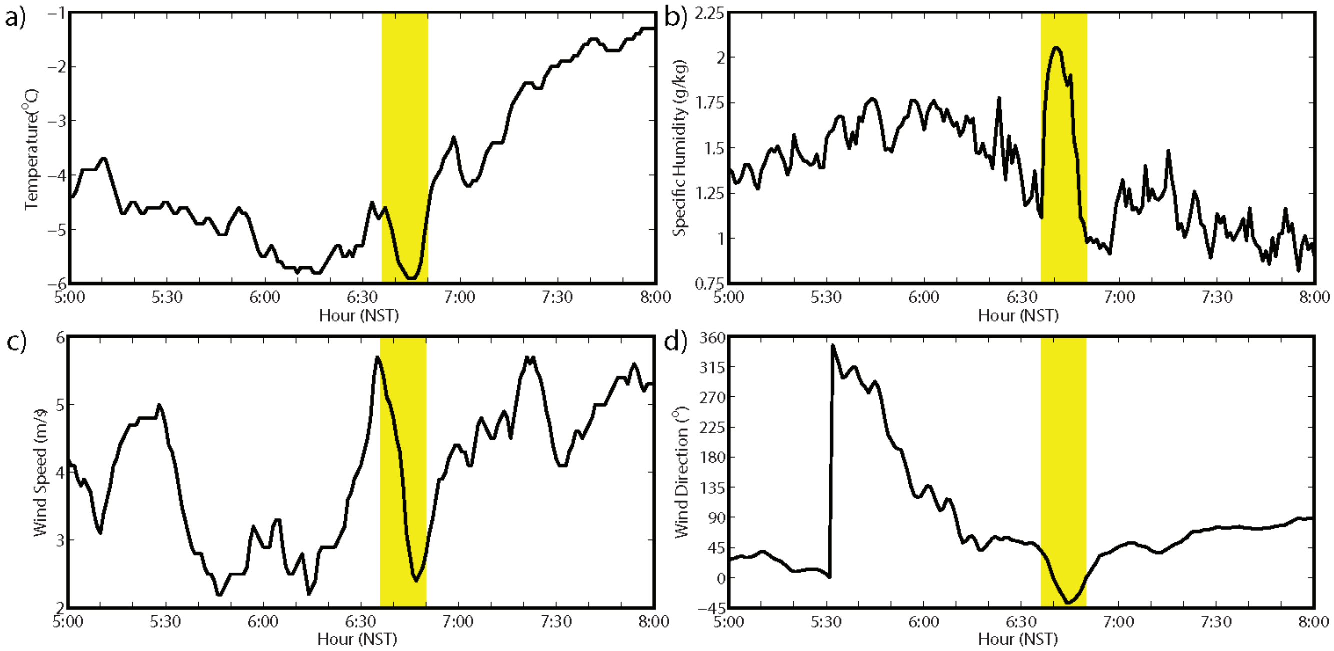

FIGURE 8. The signal of the Mount Everest avalanche as observed at the NCO-P from 5:00 to 8:00 Nepal Standard Time on 18 April 2014. Time series of (a) temperature (°C), (b) specific humidity (g kg^{-1}), (c) wind speed (m s^{-1}), and (d) wind direction (°). The light yellow indicates the period from 6:36 to 6:50 Nepal Standard Time that brackets the time of the moisture pulse and the thermal anomaly.

after 6:00 a.m. At 6:36 a.m., there was a period of approximately 15 minutes, indicated by the yellow shading in Figure 8, during which the temperature dropped before recovering and continuing to rise. During this period, the temperature fell from –4.5 °C to –6 °C. This period coincided with an abrupt increase in specific humidity from 1.1 g kg^{-1} to 2 g kg^{-1}. As was the case for the temperature, this behavior was striking in that it reversed a trend toward lower specific humidity that was taken during this time period on 18 April as well as being characteristic of the daily cycle (Fig. 7).

The period during which there was a reduction in temperature and an increase in specific humidity was associated with winds from the north, that is, wind direction less than zero. There was a maximum in wind speed of 5.6 m s^{-1} that occurred at 6:36 a.m., around the initiation time for the anomalies in temperature and specific humidity. Other wind speed maxima occurred that morning—just before 5:30 a.m. and 7:30 a.m. Neither of these maxima was associated with coherent anomalies in temperature or specific humidity.

Discussion

The avalanche that swept down the Khumbu Ice Fall on the morning of 18 April killing 16 Sherpa and injuring 9 others was one of the deadliest events in Everest's history. These deaths are consistent with studies of mortality on Mount Everest that concluded most Sherpa deaths occur in the Ice Fall as the result of hazards such as avalanches (Firth et al., 2008; McClung, 2016).

Although there is indirect evidence that avalanches are common in the Khumbu Valley (Inoue, 1977; Benn et al., 2012), direct observations of these events are rare (McClung, 2016). On the basis of photographic evidence presented in Figures 3–5, we believe these events originate as glacier avalanches that transform into powder snow avalanches as the mass of falling ice tumbles down the Khumbu Ice Fall. This transition is one of the characteristics of this class of catastrophic mass flow that occurs in glaciated environments (Pralong and Funk, 2006; Deline et al., 2015; Evans and Delaney, 2015).

We believe that the period of elevated specific humidity and reduced temperature observed at the NCO-P from 6:36 a.m. to 6:51 a.m. on 18 April was the result of a so-called avalanche wind or air blast that was triggered by this avalanche. Such winds are associated with the suspension or plume of fine ice and snow crystals that can decouple from the denser core of the avalanche and travel far downstream (Grigorian, 1975; Hopfinger, 1983; Bartelt et al., 2016). There are, however, few if any quantitative observations of this phenomenon (Martinelli and Davidson, 1966; Bartelt et al., 2016).

One particularly striking characteristic of the observed anomaly was the increase in specific humidity and decrease in temperature as it passed the NCO-P (Fig. 8). We attribute these changes to cooling associated with the sublimation of snow. Calculations in the Appendix indicate that the temperature drop associated with this sublimation is estimated to be 6 °C. The mismatch between the estimated temperature drop and the observed drop of 1.5 °C may be the result of turbulent entrainment of environmental air into the plume as it propagated toward the NCO-P site. Alternatively, if the air in the plume was drawn down from higher up in the Western Cwm, then adiabatic compression would have warmed the air prior to the sublimational cooling.

The observations indicate that as the plume passed the NCO-P, it had a wind speed of ~6 m s^{-1} (Fig. 8). As a result of surface friction, winds confined in a steep valley, such as the Khumbu Valley in the vicinity of the NCO-P (Fig. 6), tend to be at a maximum in the valley center at some height above the valley floor and tend to decrease toward valley sides (Zardi and Whiteman, 2013). As a result, it is difficult to infer the spatial details of the wind field associated with this event from the NCO-P data. However, on the basis of observations in a deep mountain valley in western Colorado, an increase in wind speed by a factor of two is likely from the sidewall to the center of the valley (King, 1989). Therefore, we estimate that the wind speeds in the center of the valley as the plume based the NCO-P were on the order of 10–12 m s^{-1}. It is not known what the wind speed was when the plume passed base camp, but assuming some frictional slowdown as it propagated down the valley, it was probably on the order of 20 m s^{-1}. Wind speeds in excess of 20 m s^{-1} have been reported as hazardous to humans (Penwarden, 1973; Hugenholtz and VanVeller, 2016) and so a wind speed of this magnitude at base camp, although high, probably did not contribute to the deaths during this event. This is consistent with reports during the event that indicated that all the deaths occurs in the vicinity of the Ice Fall and were the result of trauma associated with the collapse of the serac and the resulting movement of snow and ice (Wallace, 2014; Stokes et al., 2015)

The observations indicate that the anomaly passed the NCO-P between 6:36 a.m. and 6:51 a.m. As mentioned in the Introduction, there is some ambiguity with respect to the timing of the event; estimates in newspaper and magazine reports ranged from "around 6:30 a.m." (Barry and Bowley, 2014) to "before 7:00 a.m." (Krakauer, 2014). All these estimates are secondhand accounts obtained at a time of great stress from individuals coping with a chaotic situation. It is also unclear if the reported times referred to the initiation of the event or the time that personnel at base camp were first aware of casualties resulting from the avalanche. The most definitive first person account indicates that the avalanche occurred sometime before 6:45 a.m. and most likely earlier then 6:30 a.m. (Wallace, 2014). Assuming an average wind speed for the plume of 20 m s^{-1}, it would take approximately 8 minutes for the plume to reach the NCO-P. This timing is consistent with the event occurring before 6:30 a.m. but is clearly inconsistent with an event occurring around 6:45 a.m.

Could other atmospheric phenomenon have triggered the anomalies observed at NCO-P? Precipitation at the NCO-P tends to be associated with a relative humidity close to 100% (Bonasoni et al., 2008). The relative humidity at NCO-P during the event was ~50%, which is therefore too low for the occurrence of clouds in the region. This is consistent with the photograph of the avalanche (Fig. 5) as well as those taken during the rescue attempts later on that day that all indicate the absence of low clouds (Wallace, 2014). Based on the experience of the authors and consistent with the cold and dry conditions that occur in the region during the morning hours (Figs. 6 and 7), fog is a rare occurrence in the region and it is unlikely that a transient fog bank was responsible for the observations. The surface pressure at the NCO-P during the event was close to its climatological value and showed no evidence of an anomaly, which suggests that a transient mesoscale atmospheric phenomenon was not responsible for the observations.

High temporal resolution AWS data at the NCO-P is available for 2014 and 2015. An examination of this data during the pre-monsoon climbing season, April and May, did not identify any similar coherent anomalies in the temperature, specific humidity, and wind data. This includes the small avalanche observed on 8 April 2014 (Fig. 4) as well as the large avalanche, with an estimated volume of 50,000 m^3, that occurred on 25 April 2015 (Bartelt et al., 2016). As will be shown in subsequent work, the characteristics of this avalanche, including its source along the ridge to the north of Everest Base Camp, did not result in an avalanche wind that propagated down the Khumbu Valley past the NCO-P.

Conclusions

On 18 April 2014, the collapse of a serac situated along a hanging glacier on Mount Everest's western shoulder resulted in an avalanche that passed though the Khumbu Ice Fall, killing 16 Sherpa and injuring 9 others. This event was one of the deadliest events in the history of the region. Smaller scale avalanches occur often in the region (Inoue, 1977), but events that result in deaths or serious injuries are rare (McClung, 2016).

The AWS at the NCO-P, situated ~10 km downvalley from Mount Everest, observed anomalies in temperature, specific humidity, and wind soon after the avalanche. We propose that they were associated with the passage of an avalanche wind or air blast that transported moisture down the Khumbu Valley. There appears to be no other atmospheric phenomenon that could have resulted in such anomalies. In addition, the event is unique in the admittedly short instrumental record at the NCO-P.

Avalanches are one of the acknowledged risk factors for those who climb in the region and represents the major cause of mortality amongst the indigenous population who support climbing expeditions to Mount Everest (Firth et al., 2008). The 2014 Mount Everest avalanche and a similar one caused by the April 2015 Nepal earthquake may be indications that the hanging glaciers that ring the Everest Massif are reaching a point where their stability is at risk. Indeed, an experienced operator pulled his expedition off of Mount Everest in 2012 over concerns with the stability of the hanging glacier that collapsed in 2014 and subsequently reorganized his expeditions to minimize the time spent by climbers and support personnel in the Ice Fall (Krakauer, 2014).

These concerns are consistent with glacier mass balance calculations forced by CMIP5 climate model runs, which suggest a significant reduction, in addition to what has already occurred (Thakuri et al., 2014), in the extent of these glaciers by 2100 (Shea et al., 2015). The changes are predicted to be most pronounced around 5550 m a.s.l. (Shea et al., 2015), that is, at the height of the Khumbu Ice Fall, suggesting that these glaciers, as they continue to lose mass, will remain a significant hazard to climbers and their support teams. It is hoped that an active monitoring program inspired by these observations will allow for a better characterization of these events, thereby providing some additional degree of safety for those who venture into the Mount Everest region.

Acknowledgments

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APPENDIX

ESTIMATE OF THE COOLING OF THE PLUME BY SUBLIMATION

Assuming that the plume has a volume V, the mass of the plume M is:

$$M = \rho V, \quad \text{(A1)}$$

where ρ is the density of the plume. If q_{diff} is the difference in the specific humidity of the plume compared with the environment, then the energy E required to sublimate the moisture is:

$$E = q_{diff} \rho V L s, \quad \text{(A2)}$$

where L_s is the latent heat of vaporization. This energy must be extracted from the mass of the plume and will result in a temperature drop ΔT of:

$$\Delta T = q_{diff} \rho V L s \;/\; (c_p \rho V)$$
$$= q_{diff} L_s \;/\; c_p. \quad \text{(A3)}$$

The automatic weather station (AWS) data can be used to estimate q_{diff} as being the difference between the saturation specific humidity (5.1 g kg^{-1}) and the observed specific humidity (2.8 g kg^{-1}).