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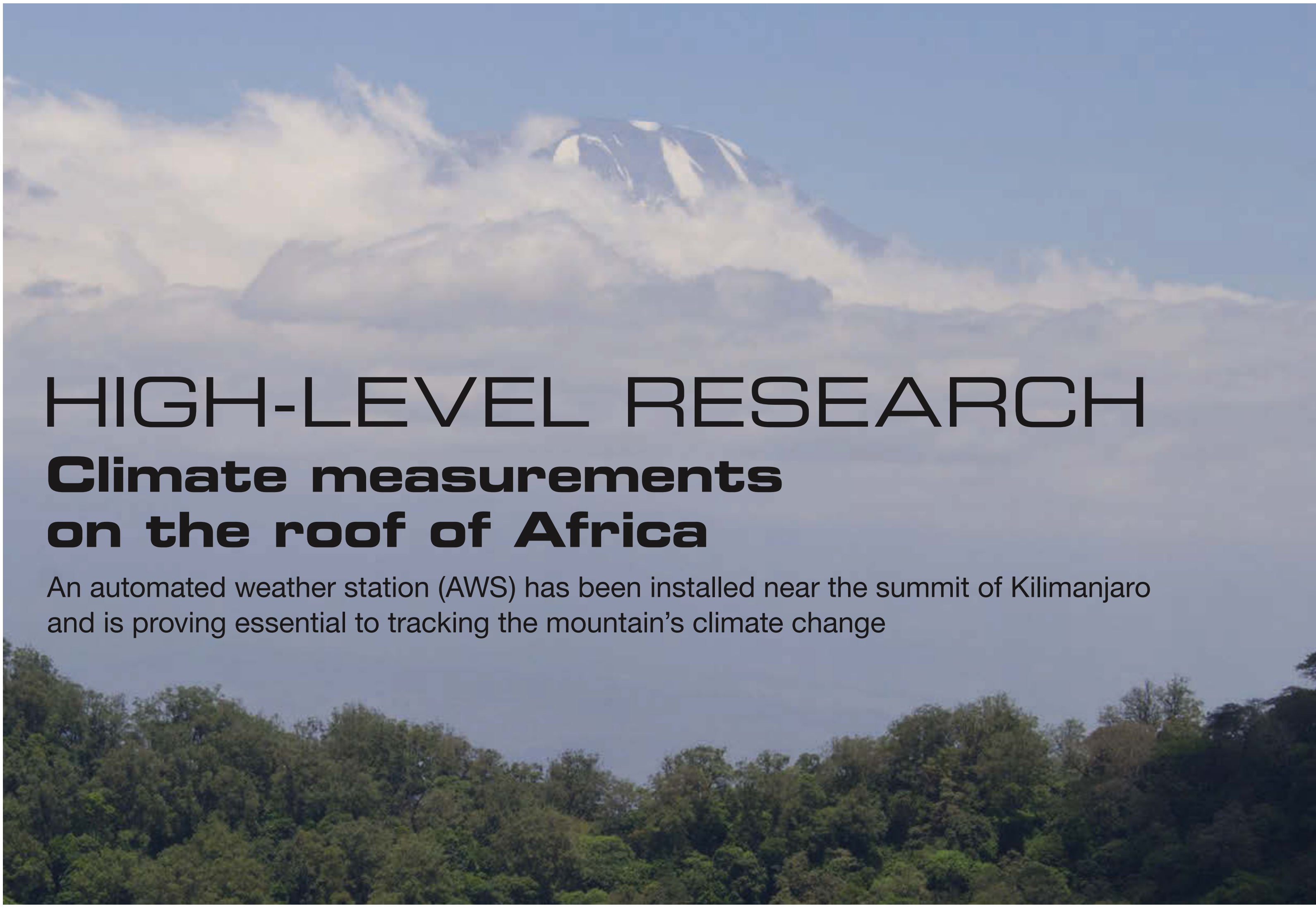
ROOF OF AFRICA

Tracking mountain climate change using automatic weather station installations

by Douglas R Hardy, PhD



HIGH-LEVEL RESEARCH

Climate measurements on the roof of Africa

An automated weather station (AWS) has been installed near the summit of Kilimanjaro and is proving essential to tracking the mountain's climate change

Figure 1: Kilimanjaro summit and south-side glaciers, appearing to float above the clouds, as seen from 60km to the west in Arusha National Park

Is Kilimanjaro a feature of Earth's surface or of the atmosphere? As initially obvious as the answer may seem, the impression one gets from either the vast, surrounding plains or from the summit is often less apparent. From either perspective, meteorological measurements we are making on the mountain at 5,775m – exactly halfway through the atmosphere at 506hPa – are providing fascinating insights into a unique climate-glacier relationship, and east Africa's tropical troposphere.

Kilimanjaro encompasses more than 3,000km^2 of northern Tanzania, with a vertical relief of 5,000m. Spending time on the mountain reveals why 50,000 people endure the crowds and expense each year, for Kilimanjaro is simply fascinating in numerous respects. Among these are a human culture that has adapted and developed over millennia, and in many respects remains intact; the friendly, cheerful people working on the mountain, who outnumber tourists 4:1; the zonation of ecological assemblages, which often change with every meter of ascent; the dramatic diurnal cycles characterizing Kilimanjaro's climate, which also changes sharply with elevation; and the incredible panoramic view from high on the mountain, typically looking down onto understory clouds but occasionally to distant peaks, lakes and human development below.

Rarely is the surrounding atmosphere quiescent; intense radiation drives convection above the slopes, which expands spatially and vertically during the day until airflow from another direction dries out the rising parcels. These features and processes are enchanting.

The summit itself is also huge, comprising a more-or-less flat caldera more than 2km in diameter. Multiple concentric 'craters' are a reminder that this is a volcano, along with elemental sulfur deposits, emissions of sulfur dioxide and steam vents – all providing clear evidence that volcanic activity has not ceased there.

Hemingway's "unbelievably white in the sun" is not hyperbole. There is little doubt he was referring to the summit glaciers, the ragged fringe of an ice cap that once encircled the broad caldera and spilled down onto the flanks. The area covered by ice has been greatly diminished from the late 19th century and continues today, yet the glaciers remain starkly beautiful against the dark volcanic ash and deep-blue sky beyond. Their color changes with the lighting, becoming brilliant white when the

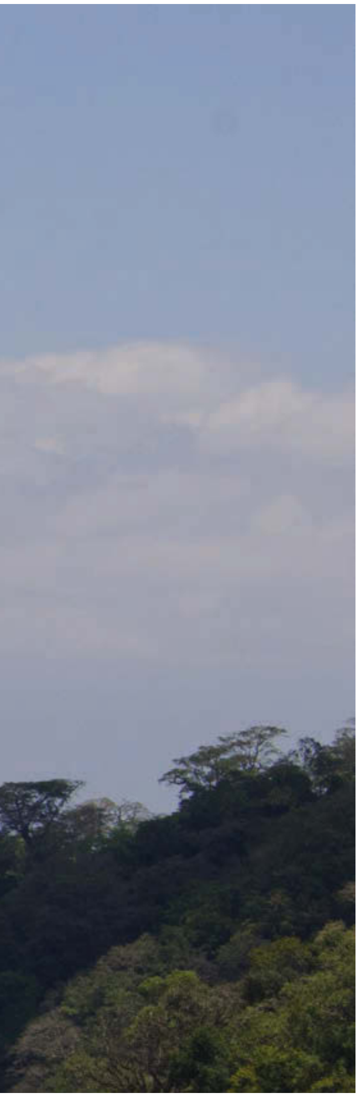


Figure 2: Panorama across the summit caldera looking over the Furtwängler Glacier remnants to the Northern Ice Field (2.3km distant), from near Uhuru Peak

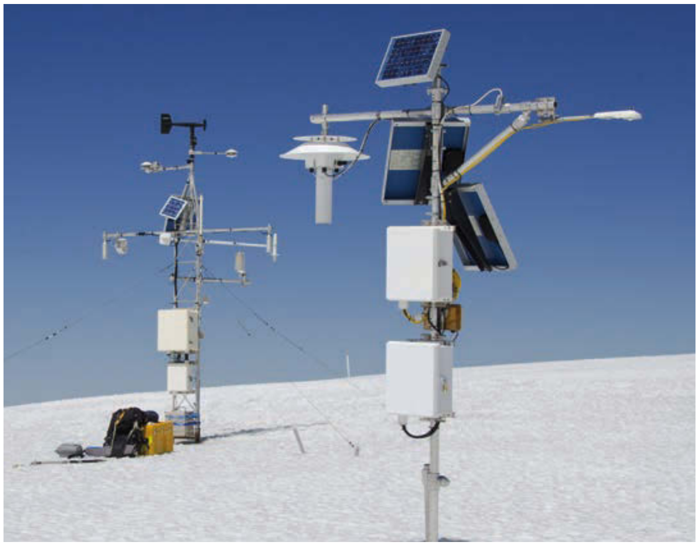


Figure 3: Automated weather stations (AWS) on Kilimanjaro's Northern Ice Field. The original AWS installed in February 2000 is on the left, including an albedometer and pyrgeometer; another tower with a net radiometer and supplemental instrumentation was added in 2010 and 2012

albedo is high and intense incoming solar radiation is reflected back.

Kilimanjaro's glaciers are still over 45m thick in places, and preserve a record of environmental change that does not exist within ice anywhere else on the African continent. In February 2000, Lonnie Thompson (Ohio State University) drilled six ice cores at the summit, and from these developed a record that may span nearly 12,000 years. At the time of drilling, no systematic meteorological measurements existed from the summit, with only a few anecdotal temperature measurements. Indeed, all existing climate stations at the time were about 4,000m lower in elevation, and their data revealed nothing about temperature, radiation, airflow or precipitation high on the mountain.

To provide a physical basis upon which to interpret the ice cores, an automated weather station (AWS) was installed during drilling, near the deepest site. The principle objective has expanded from a short-term experiment to one of comprehensively characterizing the current summit climate, which includes considerable interannual variability. Measurements are proving valuable in understanding the long-term history of Kilimanjaro's glaciers, the ice-core records, and the larger-scale causal mechanisms driving environmental changes currently underway in east Africa.

"Measurements are proving valuable in understanding the long-term history of Kilimanjaro's glaciers"

After 14 years, the glacier AWS has proved successful beyond all expectations. Although maintaining the station on a constantly changing glacier surface requires considerable effort, Kilimanjaro provides a fixed platform for continuous measurement of the tropical troposphere. Unlike transient radiosonde observations at this level, the AWS enables measurement of a broader suite of variables (e.g. radiation) and at much higher frequency. The initial station installed in 2000 included sensors to measure windspeed and direction, incoming and reflected solar radiation, downward longwave radiation, surface temperature, aspirated and naturally ventilated air temperature and humidity, snow accumulation and ablation (i.e., ultrasonic distance), and barometric pressure (Figure 3). Four-hourly values from most of these measurements are transmitted by the station via Argos satellite telemetry, which has performed flawlessly over the entire period.

In 2010 and 2012, additional sensors were installed, which are compatible with those of the USCRN (Climate Reference Network), including a continuously ventilated radiation shield housing several PRT temperature sensors and a high-accuracy, warmed humidity sensor. Also added were an infrared temperature transducer and an integrated, four-component net radiometer. Through improved measurement accuracy these sensors are yielding a comprehensive new view of the summit climate.

The success of climate measurements on the Northern Ice Field is due to a variety of factors. Some were anticipated, such as the mountain's free-standing nature and high elevation, while others were fortuitous:

• Airflow over the broad, dome-shaped glacier is minimally disrupted by topography. To the east, which is the predominant wind direction, the relatively flat snow and ice surface extends

Figure 4: This AWS on Kilimanjaro's Northern Ice Field at 5,775m has a net radiometer (left-hand side) and fan-aspirated shield for a temperature and humidity sensor (right). Mt Meru, 70km away, can be seen in the background

approximately 800m from the AWS. Windspeed averaging 6m/sec provides good ventilation of instruments – improving accuracy – yet high wind loading on the tower is rare.

• Air at Kilimanjaro's summit is typically dry, with vapor pressure averaging 2hPa and annual precipitation less than 300mm. Frequently stratiform and/or convective clouds develop around the mountain, occasionally reaching even higher altitudes, while clear sky prevails over the caldera. This donut-shaped pattern is not visible from the surrounding plains, yet is an important feature of the summit climate. Due to the dry air and intense incoming solar radiation, rime ice development on instruments is infrequent, as time-lapse camera images demonstrate. Even during the two seasonally wet periods each year, rime that does develop typically sublimates and/or falls off within hours to days (e.g. Figure 6, middle).

• Air quality on the Northern Ice Field is very high, which maintains instrument accuracy between service intervals and calibrations. Despite the large area of exposed caldera, a recent analysis of trace elements in one of the ice cores found very low concentrations of insoluble particles.

• Intense solar radiation provides an abundant power source, via photovoltaics.

• Long-term station data in east Africa is almost exclusively from elevations at least 4,000m lower than the Kilimanjaro AWS – beneath a persistent inversion layer – and therefore much less representative of both summit climate and the free atmosphere.

• Beneath the AWS, literally, is an environmental archive preserved by the glacier, currently believed to have begun forming nearly 12,000 years ago. Modern climate measurements are aiding in the interpretation of the ice core record, through improved understanding of how the glacier records climate.

Our newest measurements from the recently added net radiation sensor are particularly exciting. Until adding this instrument, each radiation component was measured separately, because engineering and spatial considerations required siting instruments close to the tower. Being too prominently within the instruments' fields of view, the tower adversely influenced measurements. Now, with the lightweight, integrated sensor, measurements are being made further from the tower and better represent the four variables (Figure 5). In addition, any leveling adjustment during fieldwork at the site (5,775m) consumes far less time than is required to level four different instruments.

The first year with an integrated net radiometer at the site demonstrates the intensity of radiation on Kilimanjaro, as the median incoming shortwave at midday – over all days of the year – was nearly 90% of that at the top of the atmosphere. Net shortwave radiation varied widely, due to control of reflectivity by surface variation in albedo, which ranged from 0.31 during the dry season to 0.90 following snowfall. In general, measurements reveal a very close correspondence between the variability of snowfall/snow-surface age and net solar radiation. Figure 7 indicates the sensitivity of net shortwave receipt to snowfall (e.g. late-September event), yet also illustrates the influence of snowfall magnitude – as shown by the gradual increase following the

Figure 5: The net radiometer and infrared temperature transducer installed on Kilimanjaro in October 2012 both view the same area of glacier surface

Figure 6: These images taken by a time-lapse camera on Kilimanjaro's Northern Ice Field illustrate the variability of glacier surface texture and albedo. Note the ablation stake in the foreground. From left to right: October 12, 2009, January 11 and February 3, 2010, all at 18:00 local time

March-May 'long rains'. During the extended dry season of June into September, gradually lowering albedo as the snow ages causes almost a doubling of net shortwave radiation, resulting in continuous ablation through the coldest months of the year (not shown).

These new radiation measurements confirm that the variability of net radiation is most directly controlling the 'health' of these glaciers. Earlier measurements, and modeling with collaborators at the University of Innsbruck (Austria), showed that Kilimanjaro glaciers are indeed primarily sensitive to the variability of snowfall amount and timing. One obvious reason for this is that snowfall adds mass to the glaciers. More importantly, it is surface brightness (i.e., albedo) that controls the extent to which solar radiation is reflected rather than absorbed Figure 6). When radiation is absorbed at the glacier surface, this energy is available to drive melt and sublimation, both of which remove mass from the glaciers and are causing shrinkage.

Details of high-elevation climate are poorly documented, yet many tropical mountains support a high degree of biodiversity. However, some ecological communities will be unable to migrate upward as quickly as the troposphere warms. Kilimanjaro affords an opportunity to make a full suite of climate measurements high above any others that exist in the region, and thus serves as a valuable tool for assessing model performance as well as measurements made at larger spatial scales by radiosondes, satellites and reanalysis data. Hopefully, Kilimanjaro measurements can continue until interannual variability is better resolved, and in the meantime collaborative investigations will continue and expand.

Operating the Kilimanjaro AWS has been a fascinating endeavor, possible only with assistance from numerous collaborators and assistants. Gratitude is particularly due to Raymond Bradley in the Climate System Research Center at the University of Massachusetts Amherst, Thomas Mölg and Georg Kaser at the University of Innsbruck, as well as Tanzanian personnel on the mountain and in governmental agencies (especially TAWIRI, TANAPA, and KINAPA). This research has been primarily supported by the US National Science Foundation (NSF); any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of NSF. ▮

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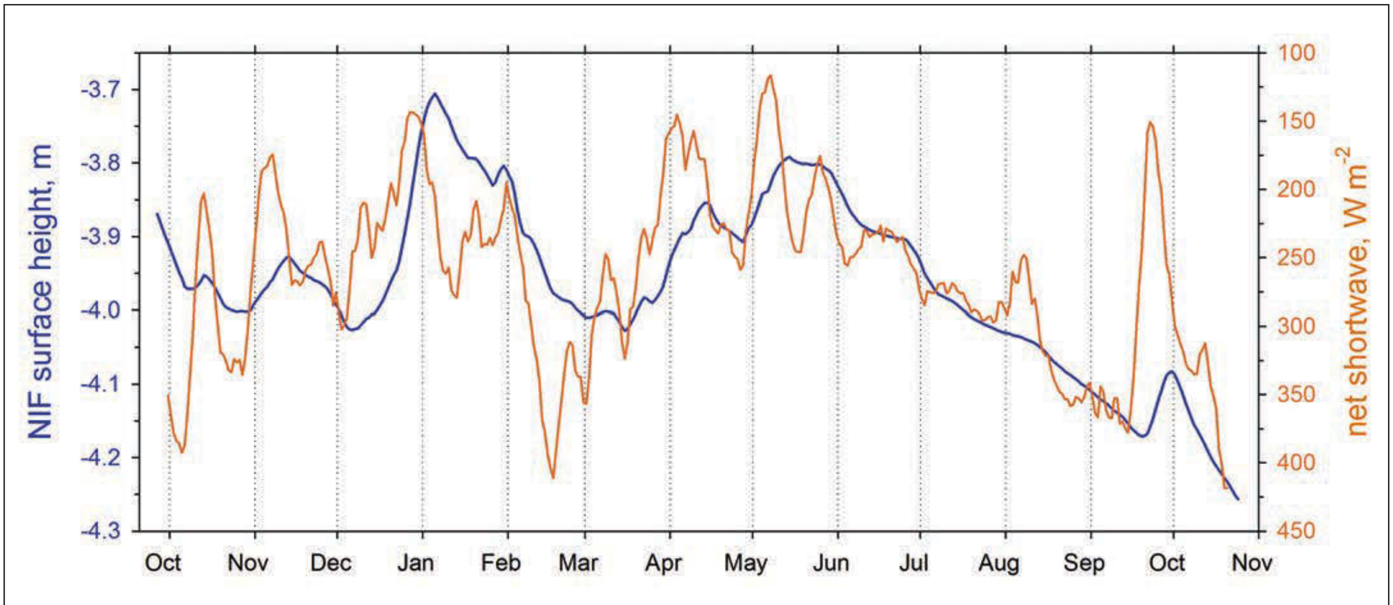

Figure 7: A time series of glacier surface height and net shortwave radiation on the Northern Ice Field, with both shown as seven-day running averages. Datum for surface height is February 25, 2000. Note reversed y-axis scale for radiation