History and Data Records of the Automatic Weather Station on Denali Pass (5715 m), 1990–2007

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ABSTRACT: We present the data records and station history of an automatic weather station (AWS) on Denali Pass (5715 m MSL), Alaska. The station was installed by a team of climbers from the Japanese Alpine Club after a fatal accident involving Japanese climbers in 1989 and was operational intermittently between 1990 and 2007, measuring primarily air temperature and wind speed. In later years, the AWS was operated by the International Arctic Research Center of the University of Alaska Fairbanks. Station history is reconstructed from available documentation as archived by the expedition teams. To extract and preserve data records, the original datalogger files were processed. We highlight numerous challenges and sources of uncertainty resulting from the location of the station and the circumstances of its operation. The data records exemplify the harsh meteorological conditions at the site: air temperatures down to approximately -60°C were recorded, and wind speeds reached values in excess of 60 m s^{-1} . Measured temperatures correlate strongly with reanalysis data at the 500-hPa level. An approximation of critical wind speed thresholds and a reanalysis-based reconstruction of the meteorological conditions during the 1989 accident confirm that the climbers faced extremely hazardous wind speeds and very low temperatures. The data from the Denali Pass AWS represent a unique historical record that can, we hope, serve as a basis for further monitoring efforts in the summit region of Denali.

KEYWORDS: Automatic weather stations; Mountain meteorology

1. Introduction

With a summit elevation of 6190 m MSL, Denali, formerly known as Mount McKinley, is the highest mountain on the North American continent. As such, it has long been popular with climbers despite its reputation for extreme cold and generally harsh weather conditions. From 1990 to 2007, an automatic weather station (AWS) was intermittently operational at Denali Pass (5715 m MSL; $63^{\circ}04.749'\text{ N}$, $151^{\circ}01.747'\text{ W}$), a col located on the West Buttress route in relative proximity to the summit (Fig. 1).

Initially a “citizen science” project without institutional support, the AWS was installed and operated for 10 years by a team of dedicated mountaineers belonging to the Japanese Alpine Club (JAC). Eventually, the station was donated to the International Arctic Research Center (IARC) at the University of Alaska Fairbanks (UAF). To our knowledge, the Denali Pass AWS was the world’s highest weather station at the time of its installation. It was the highest station in the Americas until the installation of two AWS above 6000 m MSL in the Bolivian Andes in 1996 (Hardy et al. 1998). To this day there are no continuous meteorological measurements from higher elevations in North America of which we are aware.

High-elevation AWS installations remain rare because of the combined challenges of difficult access and harsh conditions.

Existing data are all the more valuable and serve to improve understanding of important atmospheric and climatic processes (e.g., Marty and Meister 2012; Ohmura 2012; Rangwala and Miller 2012), as well as ground-atmosphere interactions, for example, in the context of local catchments, regional hydrology, and the high-mountain cryosphere (e.g., Immerzeel et al. 2014; Shea et al. 2015; Immerzeel et al. 2020; Litt et al. 2019). Data records from high-elevation mountain AWS have proven essential for delineating drivers of local glaciological processes (Salerno et al. 2015) and are important for the calibration of proxy data such as ice cores from mountain glaciers to atmospheric variability (Hardy et al. 1998; Osterberg et al. 2017; Winski et al. 2018; Bohleber 2019). Under ongoing climate change, mountain environments are changing rapidly, with potentially dramatic consequences for local populations affected by related natural hazards or downstream communities reliant on mountain-fed river systems (Hock et al. 2019; Immerzeel et al. 2020). Yet, because of the overall data sparsity at high elevations, important knowledge gaps remain, particularly in relation to elevation-dependent warming (EDW) and, accordingly, EDW as a source of uncertainty in cross-disciplinary modeling efforts (Rangwala and Miller 2012; Pepin et al. 2015).

Furthermore, weather is a key determining factor for the successes and failures not only of climbers’ summit bids on Denali, but for all aspects of on-mountain operations. Accurate information on current conditions at high elevations—which may differ substantially from those at lower elevations—is crucial for risk assessment. Real time in situ meteorological observations from AWS networks improve the safety of climbers and support teams at altitude. In addition to providing support for real-time decision-making, AWS data can increase the

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FIG. 1. Overview of the Denali summit area with the location of the Denali Pass AWS and climbing camps along the West Butte route (the photographs were provided through the courtesy of M. Stuefer, taken in May 2015). The map shows the hill shade and contours generated from a digital elevation model with $5\text{ m} \times 5\text{ m}$ resolution (U.S. Geological Survey 2014a,b).

accuracy of weather forecasts for point locations in complex terrain, based, for example, on model output statistics applications (e.g., Hart et al. 2004; Cheng and Steenburgh 2007; Ghirardelli and Glahn 2010; Matthews et al. 2020). Alaska lacks high-resolution regional weather forecast models and is generally data sparse. Accordingly, there is much room for improvement in this area and developing a dedicated forecast to inform operations on Denali would be highly desirable. Expanding the existing AWS network in Denali National Park to the summit region would be an important step toward this goal and we hope that the experiences gained during the Denali Pass AWS project will aid this effort.

The main aims of this publication are to 1) give an overview of the history of the Denali Pass AWS as well as challenges

encountered due to the circumstances of its operation and the characteristics of the site and 2) comprehensively present the data that were collected by the AWS to ensure the preservation of historic records and their availability to the interested community. We begin by providing a summary of the events that led to the installation of the station and a brief history of meteorological measurements on Denali. This is followed by a description of the Denali Pass AWS setup that is based on a review of historic expedition records and archived communications among the JAC team. We then present the data extracted from the original datalogger files—mainly wind speed and temperature—alongside a comparison with atmospheric reanalysis data. We approximate a threshold for wind speeds that are dangerous to climbers and give an overview of the weather conditions during the fatal accident of a Japanese

team in 1989. A brief discussion is followed by the main conclusions from the Denali Pass AWS project.

a. Motivation for AWS installation

On 20 February 1989, a three-person team of Japanese mountaineers climbing the West Buttress route reached High Camp at 5243 m MSL. The team leader, N. Yamada, was hoping to become the first person to summit the highest peaks of the seven continents in winter and was climbing with two other experienced mountaineers, T. Saegusa and K. Komatsu, on this occasion. At High Camp, they met a descending team. Both teams remained in camp on 21 February because of severe weather. On 22 February, the weather briefly cleared, and the second team continued their descent while the Japanese group remained in camp. Soon after, the weather deteriorated once more. The Japanese team was not seen alive or heard from again. Search flights spotted their bodies on 10 March below Denali Pass. Later in March, a 17-person team from the Japanese Alpine Club recovered the bodies. Hypothermia was determined as the cause of death. Referring to the incident, the National Parks Service (NPS) mountaineering report of 1989 states, “It is believed that the climbers tried for the summit during a brief lull in the severe wind storm and were caught near Denali Pass as the winds again increased” (Denali National Park Service 2020).

In the aftermath of the fatal accident of the Japanese team, a debate on the causes developed within the Japanese mountaineering community and questions were raised as to the decision-making of the team leader. A group led by Y. Okura of the Japanese Alpine Club—himself an accomplished mountaineer—argued that extreme wind speeds likely caught Yamada and his companions by surprise and that the accident was not the result of a lack of mountaineering experience. Okura set out to prove that gusts on Denali Pass reach wind speeds so extreme that climbers can literally be “blown off the mountain.” To this end, Okura led the efforts to install and maintain a weather station at Denali Pass.

b. AWS location and previous meteorological measurements on Denali

Denali Pass lies north of Archdeacon’s Tower (5974 m MSL) and Denali’s main summit (6190 m MSL), and south of Denali-North Peak (5934 m MSL)—a subsidiary summit of Denali. It forms a west–east-oriented col and constitutes the ice divide between the glacier system of the West Buttress to the west and Harper Glacier to the east. On the western side of the col, the terrain drops off sharply into a steep, glaciated slope and the glacial plateau of High Camp farther below. The drop-off to Harper Glacier is less pronounced. Figure 1 shows an overview of the Denali summit area and the location of the AWS. The AWS was situated slightly higher than and south of the low point of the pass on an outcrop with exposed rock that allowed for more secure anchoring of the station.

In the climbing community, Denali is notorious for the extreme weather conditions that often prevent mountaineers

from reaching the summit. Much of Denali’s famously “bad” weather can be attributed to latitude and regional topography. Denali is a relatively isolated peak with a prominence of 6144 m, and, at 63°N, it lies within the influence of the polar front and associated storms that tend to develop in the Bering Sea. An overview of typical synoptic patterns that affect weather and climate on Denali can be found in Hartl et al. (2020a) and references therein. In 1952, B. Washburn, a pioneer of Denali mountaineering and director of the Boston Museum of Science, wrote in *Weatherwise* magazine, “McKinley is probably one of the coldest and most savage spots on earth” and attributes his group’s success on the mountain to a “sound knowledge” of the changeable local weather (Washburn 1952). In the same publication, Washburn states that a minimum-registering thermometer, weighted with rocks, that his team left at Denali Pass from 1947 to 1951 recorded -59°F (-50.6°C) as the absolute minimum temperature for that time period. In 1913, the team of the Stuck expedition—the first to successfully reach the summit—took multiple temperature readings along their route and left a minimum-registering thermometer at Parker Pass (~ 4570 m MSL). This was recovered 19 years later, in 1932, by the Lindley–Liek expedition (Washburn 1952). The instrument was graduated to -95°F (-70.6°C) and was found stuck in a position indicating that temperatures had dropped below this value. However, there was some doubt as to whether the thermometer was “exposed properly” (Frost 1934).

In more recent times, sporadic meteorological measurements on or near Denali have been carried out in the context of glaciological studies at lower elevations, for example, on the Kahiltna Glacier (Young et al. 2018), or for brief periods of time during scientific expeditions, for example, on the summit plateau of Mount Hunter during the drilling of glacial ice cores (Winski et al. 2018; Osterberg et al. 2017; Saylor et al. 2014). Winski et al. (2018) use temperature data collected in 2013 and 2015 on Mount Hunter to determine the distribution of summer temperatures at the drill site, which informs the analysis of melt layers in the ice core and the development of a long-term temperature record, providing valuable insights into Holocene climate in the Denali region and beyond. The ice core analysis suggests a summertime warming rate of $1.92^{\circ} \pm 0.31^{\circ}\text{C}$ in the last century, which exceeds typical warming rates at lower-elevation sites of similar latitude and is in the same range as a temperature increase of $0.02^{\circ}\text{C yr}^{-1}$ found by Hartl et al. (2020a) from NCEP–NCAR reanalysis data (Kalnay et al. 1996). Comparing summer temperatures from Mount Hunter with data from the Denali Pass AWS might contribute to the expansion of the temperature distribution time series and aid in the analysis of future ice core samples from the Alaska Range, which in turn would be greatly beneficial to improving the understanding of the complex interplay of EDW at high latitudes, cycles of teleconnections like the Pacific decadal oscillation, and changes in North Atlantic Ocean storm tracks that shape the region’s weather and climate.

At present, the NPS maintains an AWS network in Denali National Park, mostly at mid- and low-elevation sites. In 2018, NPS installed weather stations at Denali Base Camp (2195 m MSL) and Medical Camp (4267 m MSL). The AWS at Medical Camp

FIG. 2. The Denali Pass AWS in 1990 (photograph provided through the courtesy of Y. Okura/JAC) and during maintenance expeditions carried out by the UAF team, from 2003 to 2007 (photographs provided through the courtesy of T. Saito).

is the highest continuously measuring station in the park to date, aside from the Denali Pass AWS.

2. The Denali Pass weather station

The initial Denali Pass AWS was installed in June 1990, was significantly updated with a new instrument stand in 1992, and was donated to the IARC at the University of Alaska Fairbanks in 1999. The installation—as well as the entire planning effort and preparation of instrumentation preceding the initial installation—was carried out by mountaineers from the JAC, led by Mr. Okura.

The station was operational intermittently until 2007 and recorded data continuously during periods of up to several months, mainly in the summer seasons. Between 1990 and 2008, members of JAC and IARC personnel collaborated on joint expeditions to maintain and repair the station, with support from NPS rangers. Maintenance expeditions were typically carried out in late May or June. The 2007 expedition found that the instrument stand had collapsed because the supporting poles had been bent and all antenna cables had broken. Attempts to repair the station in 2008 were prevented by severe weather, and the project was subsequently abandoned.

To reconstruct the station and instrumentation history, expedition records and photographs, as well as old email communications among the team were viewed, and members of the expedition teams were contacted where possible. Because of the circumstances of the station installation and maintenance, standard meteorological protocols, for example, with regard to radiation shielding of temperature sensors and systematic metadata recording, were not always followed. Not all expedition notes, particularly from the early years of AWS operation, were archived. Internal email communications of the JAC team pertaining to the instrumentation of the AWS were partially saved as text files. These emails contained text in both English and Japanese, and unfortunately the encoding of the

Japanese characters was not preserved in the text files, so information contained therein was lost.

The following description of the instrumentation at the Denali Pass AWS and respective times of operation was obtained from the sources listed above and represents an “as complete as possible” overview of the station history. Figure 2 shows photographs of the AWS in 1990 and during the time when UAF managed operations. A tabular overview of when each instrument was used can be found in Table 1.

a. Instrument stand

The initial instrument stand installed in June 1990 had a square cross section and was constructed from four iron angles joined by crossbars (Fig. 2). It was secured with pitons and guy wires, because NPS discouraged the use of bolts. The initial stand was designed and assembled by Mr. Okura, who prioritized compactness and low weight since the stand needed to be carried to the station location. Because of time pressure, the complete station setup was not tested prior to installation, and Okura states that “in hindsight, it was not a perfect piece of equipment.” Documentation by the JAC team speculates that the stand was blown over in November 1990. The maintenance expedition of the following year found several guy wires broken, one of the pitons pulled out, and instrumentation destroyed.

From the experiences with the first stand construction, a new design was subsequently created by the team of Dr. Uchiyama at Keio University, Japan. Goals for the new stand were easy assembly, light weight, and improved durability. To this end, a trapezoidal pyramid shape was chosen instead of the previous quadrangular tower, and the construction used poles instead of angle irons. A diamond-shaped joint was used to secure 30-mm duralumin poles, which were fastened by U bolts to allow for adjustments during the installation (stand shown in Fig. 2). The climbing team practiced the assembly of this stand multiple times to guarantee that they would be able to do so under difficult conditions on Denali. Meteorological instrumentation

TABLE 1. Instrumentation used at the Denali Pass AWS. Year numbers indicate the period between maintenance expeditions, from June to June of the following year.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Nakaasa	X																
Makino AG860			X	X	X	X	X	X	X	X	X	X		X			X
Makino VR236			X	X	X	X	X	X	X	X	X	X		X			X
R.M. Young 05103					X	X											
Met One model 50:5													X		X		
Vaisala WS425 A1														X		X	X
Delta-OHM-3-axis wind sensor																X	
Temperature in plastic bottle	X	X															
Temperature in metal tube			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pressure	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

was tested prior to deployment mainly by subjecting sensors to low temperatures in freezers or cold rooms and running field tests in Japan and, in later years, at the UAF campus and the signal relay station in Cantwell, Alaska. While this ensured that all components were functional, it did not fully simulate the range of conditions on Denali, particularly in terms of wind speed.

In 1992, the new stand was successfully installed. After arriving at High Camp, the installation took three days as the team was hampered by cold and windy weather. With permission from NPS, the new stand was secured with bolts. Okura notes that the installation of the second stand was challenging, primarily because of the weight of the equipment. The stand and tools weighed approximately 100 kg. Combined with personal gear and food, each of the four team members involved in the installation of the second stand had to move a load of about 60 kg. The long poles of the stand construction were cumbersome to pack, which posed an additional challenge. Up to Motorcycle Hill Camp (3350 m MSL), loads were mostly pulled on sleds. From there on, the equipment was carried in multiple trips to the higher camps. In total, the installation team spent 19 days on the mountain, from 9 June until 28 June 1992. The return trip was delayed by 3 days as a result of an eruption of Mount Spurr, which impeded air travel in the region. That the installation team consisted of only four people highlights the magnitude of their achievement and the limited resources of the Denali Pass AWS project. A comparison with the recent installation of a state-of-the-art AWS network on Mount Everest is enlightening in this regard. The highest Everest station was installed by a team of 22 people (Matthews et al. 2020).

Members of maintenance expeditions from later years report that, in addition to the effects of altitude and complications inherent to the route (e.g., crevasses and breaking trail in deep snow), the main practical problems encountered when working on the station were the wind and cold, which made it challenging to handle smaller pieces of equipment, such as U bolts, even on generally favorable days. In the later years of AWS operation, it was sometimes possible to transport equipment on NPS resupply flights by helicopter to Medical Camp. Aside from issues related to mountain travel and equipment, records from organizing UAF team members also

note significant difficulties in obtaining continued funding for the AWS upkeep and the annual maintenance expeditions.

b. Temperature

Standard platinum thermistors were used to record temperature. At the time of the initial AWS installation in 1990, one temperature sensor was inserted into a plastic bottle and mounted on the stand at 120 cm above the snow. Another sensor (not in a bottle) was inside the datalogger box buried in the snow. After retrieving the data in the following year, it was found that the plastic bottle did not provide adequate protection from sunlight and temperatures recorded in the bottle were likely much higher than ambient air temperature. From 1992 onward, temperature sensors were inserted into narrow aluminum pipes and mounted on the stand at 150, 80, and (in some years) 10 cm above the snow, with an additional sensor in the datalogger box.

The aluminum pipes were used in an attempt to recreate thermistor-tube mounts thought to be used at Arctic sites (M. Kobayashi, JAC team member, 2019, personal communication; no further explanation or information on similar mounts at any sites could be found). Unlike standard housings for temperature sensors, the housing pipes were not ventilated and were not painted white. Figure 3 shows one of the aluminum pipes from the Denali Pass AWS.

To assess the effect of the piping, an experiment was carried out in 1998 on the roof of the Hakusan Corporation building in Fuchu, Tokyo, Japan. An unshielded sensor, two sensors in nonventilated pipes, and one sensor in a ventilated pipe were installed and monitored for a 2-week period in May 1998. The unshielded sensor, mounted at about 180 cm above ground, at times recorded temperatures more than 6°C above those recorded by the aspirated sensor, which was mounted closest to the ground. The two nonventilated pipes were mounted between the unshielded sensor and the ventilated pipe. The sensor in the upper pipe recorded values close to those of the unshielded sensor, while the lower pipe showed about half the increase of the unshielded sensor, relative to the values from the ventilated sensor.

It is not clear if the difference between the two sensors in pipes was primarily due to instrumental variability or to the

FIG. 3. One of the aluminum pipes used as housing for the thermistors at the Denali Pass AWS.

difference in height above the roof. In email communications from the time, the project team speculates that the differences might be slightly less on Denali where the sun angle is lower and the wind is stronger. They conclude that temperatures measured at the Denali Pass AWS are accurate only to about $\pm 3^{\circ}\text{C}$. Once the magnitude of the error due to insolation and housing became apparent, efforts to correct for the much smaller effect of ambient temperature on the internal resistors of the sensors were abandoned.

In 2003, 2004, and 2005, during UAF operations, an AD590 temperature sensor (Analog Devices 2013) was installed in the same aluminum pipe housing as before. The AD590 remained in use in the datalogger box from 2006 onward, and a Climatec sensor (model unknown) was mounted on the mast.

c. Wind

A Nakaasa wind speed and direction sensor (model unknown) was the first anemometer of the Denali Pass weather station (Fig. 2). It was mounted during the initial installation of the station in summer 1990 and recorded data until November 1990, when the stand was blown over.

For the majority of the station's life span, Makino AG860 cup anemometers and Makino VR 263 wind vanes (http://www.makino-ohyo.jp/product/high_winds/pdf/S-VR-AGcata.pdf) were used to measure wind speed and direction. In some years, two sets of the Makino instruments were mounted at different heights (80 and 150 cm above the snow) on the stand. A Hakusan WS-104 signal converter was used to convert the resistance measurement output from the wind vanes to values in volts, which were then recorded by the dataloggers. All of the Makino anemometers and wind vanes were Teflon coated to inhibit rime ice accretion. Additionally, the cup anemometers were modified to better withstand the extreme conditions. Modifications included changing the arm material from brass to stainless steel, an increased head diameter, and reinforced mounting brackets. Nonetheless, the Makino anemometers were usually destroyed within a year and yielded little usable data.

In 1994, an R.M. Young anemometer (model 05103, marketed in Japan by Kona Systems; R.M. Young 2005), with attached temperature and humidity sensors and its own built-in datalogger (which recorded wind speed in meters per second) was installed on top of the stand. This anemometer disappeared from the stand and could not be found when the maintenance expedition arrived in June 1996.

When the UAF team took over station maintenance in 2002, multiple efforts were made to install ultrasonic wind sensors. Initially, a Met One Model 50:5 anemometer was used. It was found that it was not calibrated for sufficiently high wind speeds, and the instrument was removed for recalibration during the 2003 maintenance expedition. It was reinstalled in a refurbished and recalibrated version in 2004, together with a Davis cup anemometer that was intended for further calibration attempts but never functioned. The standard wind speed range of the Met One 50:5 as given by the manufacturer is $0\text{--}50\text{ m s}^{-1}$, for temperatures between -40° and $+55^{\circ}\text{C}$ (Met One Instruments, Inc. 2019). The instrument failed soon after reinstallation in 2004, likely because of a short circuit.

In 2003, when the Met One instrument was removed, a Vaisala WS425 A1 ultrasonic anemometer [range: $0\text{--}65\text{ m s}^{-1}$, with accuracy $(0\text{--}65\text{ m s}^{-1}) \pm 0.135\text{ m s}^{-1}$ or 3% of reading; Vaisala 2010] was installed and the Makino instruments were also made operational again. These instruments were removed in 2004 and reinstalled again in 2005 after the failure of the Met One anemometer. Also in 2005, an additional anemometer (Delta Ohm HD2003; <https://www.deltaohm.com/en/wp-content/uploads/document/DeltaOHM-HD2003-three-axes-anemometer-datasheet-en.pdf>) was installed as part of an overall effort to achieve two completely independent, redundant subsystems. Records indicate that both sensors experienced significant problems from icing. The Delta OHM instrument was found to be damaged and was removed in 2006. The efforts to achieve redundancy were hampered by radio telemetry failures and were abandoned.

In the following sections, records from the R.M. Young and Vaisala instruments are discussed further. Both instruments recorded momentary wind speed at 30-min intervals, as opposed to 30-min average wind speed. For the R.M. Young anemometer, the exact scan interval at which the instrument sampled is unknown because the logger code was not preserved. Documentation indicates that wind speed was sampled for a brief interval of a few seconds—likely a value between 1 and 10 s. The Vaisala anemometer took 3-s samples recorded every 30 min. According to documentation by the JAC team, this approach was chosen to preserve battery life and in hopes of recording extreme gusts rather than average wind speeds.

d. Air pressure

A Vaisala PTA427 pressure gauge was initially installed in the datalogger box, with a tube leading to the outside to ensure that it would be exposed to the outside air. It was modified by the Makino Instrument Company in Japan for high altitudes by changing an internal resistance. With the modification, Makino specified a pressure range of the instrument

from 400 to 1000 hPa. From 2003 to 2005, during UAF operations, a different pressure sensor was in use (model unknown).

e. Dataloggers and transmission

The Japanese team used Hakusan Datamark LS-3000PtV dataloggers for the majority of their time maintaining the station. Older LT-2001 loggers were used only during the first year of operations. The LS-3000PtV loggers had the capacity to record data on eight analog and three pulse channels simultaneously, but it was decided that not all channels should be used in order to save enough memory for a full year of observations. Lithium batteries were organized into battery packs consisting of 8 AA lithium batteries each. One pack was required for each datalogger, one for the signal converter, one for the peak signal hold unit (when used) and one for the air pressure sensor. On the mountain, the dataloggers were placed in a Styrofoam box, wrapped in aluminum-coated hard foam sheeting and then in vinyl plastic sheeting, and then buried in snow. Hitachi Maxell ER-6 lithium batteries were used until 1996, when they were replaced by Tadiran TL-2100 batteries. Fresh batteries were installed during each maintenance expedition. Records from the JAC team state that “the batteries all performed well.”

The June 2000 expedition found that all of the cables between the sensors and the dataloggers were cut (“cut” is the word used in the documentation by the Japanese team; it is not clear whether this implies an intentional cut or broken cables due to the harsh conditions) and that the insulation had partially worn off the cables. Documentation indicates that the cables generally suffered from icing, high wind speeds, and UV exposure during the entirety of the station’s life span. The 2000 expedition retrieved the sensors from the stand, and station operations were passed on to IARC/UAF after this expedition.

Real-time data transmission was attempted starting in 2002, when the UAF team assumed operations at the station. A low-power telemetry system was developed for use at the Denali Pass AWS station by Polartronix (<http://www.polartronix.net/polarpp.html>). From 2004 onward, two redundant transmission systems (satellite transponder and radio transmitter with relay station in Cantwell) with independent power supplies were employed. Nonetheless, real-time data transmission failed repeatedly.

3. File format and data processing

From 1990 to 1999, during station operation by the JAC team, data were stored on multiple dataloggers at the AWS, and collected during the annual maintenance expeditions. For each datalogger, monthly data files contain the respective channel output. Data files were initially stored as Lotus 1-2-3 (Lotus Software) spreadsheets, which were converted to comma-separated-values (CSV) format for the purpose of this publication. Processing these files posed a number of challenges: Neither the individual dataloggers nor the logger channels were used consistently for the same output parameters throughout the years and there is limited documentation of respective changes, as well as on the meaning of parameter abbreviations in the files. Additionally, three

different time zones (Alaska local time, Japanese local time, and UTC) were used for logger time stamps over the years. Time-zone information was documented in some years but not in others. We homogenized the time stamps to UTC based on comparisons of average diurnal temperature cycles for seasons with known time zones and seasons with unknown time zones, that is, by inferring the time zone from the timing of the solar-driven diurnal temperature cycle.

Temperature was recorded at up to three different heights on the mast, as well as in the datalogger box. Documentation by the Japanese team states that temperature sensors were mounted at 150, 80, and 10 cm “above the snow” but there is no information on snow depth or how this relates to height on the mast. The height of the individual sensors was not recorded in the datalogger files and the naming of the respective temperature data columns is inconsistent.

The available temperature T data were viewed and roughly screened for records that were obviously faulty (“flat” readings at constant temperature over prolonged periods of time) and erratic data (single outliers at physically highly improbable values, e.g., $T > 30^{\circ}\text{C}$). The resulting data are shown in the top panel of Fig. 4. In a further processing step, warm spikes associated with the maintenance expeditions were removed. Sensors were tested in the tents and/or warmed by being handled during reinstallation, and therefore the first readings after maintenance are atypically high and are not representative of air temperature on the mast.

With the aim of providing consolidated time series of temperature from the Denali Pass AWS, we focus on the temperature record from the datalogger box and air temperature as recorded by sensors on the mast. The former is largely identifiable by consistent naming in the datalogger files and the dampened diurnal amplitude due to the insulation of the box and the snow cover. The records from the sensors on the mast are not always named consistently, and documentation of which sensor corresponds to which height “above the snow” is incomplete. The bottom panel of Fig. 4 shows what we consider to be the most consistent time series of mast temperatures that we can extract from the datalogger files. This is mostly composed of records from what documentation suggests to have been the highest sensor on the mast. For seasons for which this record was not available, was not clearly identifiable in the datalogger files, or appeared to be faulty, gaps were filled with data from the next highest sensor depending on availability. Records from the time period after 2000, when UAF took over operations, contain only two sets of temperature data—one from the datalogger box and one from an unknown position on the mast.

The wind data measured by the JAC team with the Makino sensors (Table 1) was recorded in volts. Reliable information on the conversion factors to meters per second for the individual sensors is not available and prolonged periods of “flat” readings at constant values throughout all periods of recordings suggest systematic problems with the measurement setup. Wind speed recordings in meters per second from the R.M. Young anemometer are available from mid-June 1994 through May 1996. The Met One ultrasonic anemometer installed by the UAF team recorded data from mid-June 2002 until the end

FIG. 4. (a) Temperature data as recorded in the log files (different colors represent different dataloggers or parameter abbreviations in the log files). Extreme outliers were removed. (b) Consolidated time series of air temperature on the mast (black) and temperature in the logger box (gray). Warm spikes associated with maintenance of instrumentation were removed.

of the year. The Vaisala instrument that replaced the Met One sensor recorded from June 2003 until June 2004. Wind direction was also recorded during the 2003–04 season and for a brief period of time in the following year, although the latter readings appear to be highly erratic. (The readings from the R.M. Young and Vaisala instruments are presented in Fig. 8, described in more detail below.) A small number of physically impossible readings (negative wind speed) were deleted; otherwise, no corrections were applied. In further analysis (section 4b), we discuss the data recorded from 2003 to 2004 by the Vaisala instrument in a general manner and focus quantitative analysis of thresholds for dangerous wind speeds on the data recorded by the R.M. Young anemometer, as sonic anemometers like the Vaisala are known to be susceptible to large errors in conditions prone to icing (Makkonen et al. 2001).

Air pressure data are available for the 2003–04 record period. Air pressure was otherwise not recorded, or reliable data processing was impossible because of lack of metadata and documentation.

4. Denali Pass AWS data

In the following, we present descriptive statistics for the data recorded at Denali Pass AWS. Additionally, station data are compared with ERA5 reanalysis data for the period 1979–2019 (Copernicus Climate Change Service 2017; Hersbach et al. 2020). This reanalysis dataset is available on a 2.5° latitude by 2.5° longitude grid. Air temperature, geopotential height (GPH), and u and v wind components were extracted at the 500-hPa level for the grid cell containing Denali. Daily mean values of air temperature and GPH were computed from hourly reanalysis data. For the AWS data, daily mean temperatures were computed as the arithmetic mean of all

temperature records from a given day. Logging intervals are 30 or 60 min, depending on the year.

a. Temperature

The large uncertainties (up to $\pm 3^\circ\text{C}$ according to estimates by the JAC team) associated with the air temperature data resulting from the nonstandard mounting of the sensors in the unventilated metal tubes need to be kept in mind when discussing this time series. The lowest temperatures recorded at the Denali Pass weather station reached approximately -60°C and were recorded during a several-day cold snap in late November/early December 2003. Diurnal temperature amplitudes are highest in late spring and summer, reaching mean values of $8^\circ\text{--}10^\circ\text{C}$ during the main climbing season (April–July), and are lowest in the winter months with about 5°C . June, July, and August are the warmest months, with mean temperatures above -20°C . From December to March, monthly mean temperatures are relatively constant at about -38°C (Table 2). Figure 5a shows mean diurnal temperature cycles for each month of the year, that is, data were grouped by month and hour and averages were taken over the resulting data bins. The differing number of available records per bin was not taken into account. This figure is intended as a general overview of the characteristics of diurnal temperature throughout the year. As incoming solar radiation decreases in autumn, so does the solar driven diurnal temperature amplitude. Relative to November and the winter months, October is still comparatively warm but already shows a strongly reduced amplitude. In contrast, March is colder overall, with nighttime lows in the same range as the winter months, but the spring sun already causes pronounced diurnal warming.

The measured temperatures and the reanalysis data are highly correlated, with Pearson correlation coefficients of daily mean temperatures of around 0.9 for all seasons (daily mean

TABLE 2. Mean daily temperature amplitude, highest daily maximum, lowest daily minimum, mean daily temperature as measured at the Denali Pass weather station, split by months. Corresponding ERA5 reanalysis air temperature data at the 500-hPa level are given for comparison. AWS values were computed on the basis of all available AWS data. Reanalysis values are given for the 1979–2019 period. All values are in degrees Celsius.

Month	Mean daily amplitude (°C)	Highest daily max (°C)		Lowest daily min (°C)		Daily mean (°C)	
	AWS	AWS	Reanalysis	AWS	Reanalysis	AWS	Reanalysis
1	5.1	−24.3	−18.2	−52.3	−46.9	−38.9	−32
2	5.9	−22.9	−17	−54.1	−48.9	−38.9	−31.9
3	7.3	−22	−18.3	−49.8	−45.4	−38	−32.3
4	9.4	−18	−16.5	−46.5	−43.8	−33	−30.5
5	9.2	−17.1	−13.6	−39.6	−37.6	−26.6	−26
6	9.3	−9.2	−11.6	−26.8	−30.7	−18.5	−21.3
7	9.8	−3.8	−9.7	−27.2	−28.8	−17.6	−18
8	8.7	−9.2	−7.8	−33.5	−30.6	−19.8	−18.8
9	7.1	−11.7	−11.5	−41.8	−37.6	−26	−23.3
10	6	−13.8	−10.5	−45.7	−42	−32.4	−28
11	5.5	−18.9	−15.3	−57.4	−45.2	−36.8	−31
12	5.6	−23.6	−15.3	−57.3	−46.3	−38.6	−31.7

temperature from the AWS was compared to reanalysis for yearly intervals from 1 June to 31 May of the following year). The reanalysis data tend to overestimate temperatures in the winter, from about October to April, and match the measured values more closely in summer (Table 2, Fig. 5b). We apply a simple linear regression to the AWS data (excluding the years in which the temperature sensors were housed in a plastic bottle) and corresponding reanalysis values to generate a corrected reanalysis time series that accounts for this

overestimation of low temperatures. Figure 6 shows daily mean temperatures computed from the station data for each period in which the station was operational, as well as uncorrected and corrected reanalysis air temperatures. We speculate that the discrepancy between reanalysis and AWS data for low temperatures results from ground level radiative cooling that is not resolved in the 500-hPa reanalysis data, but more data (in situ radiation measurements) would be required to determine this with certainty.

FIG. 5. (a) Mean diurnal temperature cycles by month, aggregated from Denali Pass AWS data. (b) Comparison of the mean annual temperature cycle of AWS data (gray line) and 500-hPa reanalysis air temperature (black line), derived from daily average temperatures of the ERA5 dataset for 1979–2019 and daily averages from the AWS when available. The gray dashed line denotes in how many years AWS observations from each day of the year were available.

FIG. 6. Daily mean temperatures (thick gray line) as measured at the Denali Pass weather station for all periods during which the station was operational, daily mean reanalysis air temperatures computed from hourly data for the 500-hPa level of the Denali grid cell (thin black line), and corrected reanalysis (dashed black line).

For the 2003–04 season, the only period during which air pressure was successfully recorded at the Denali Pass AWS, the correlation between measured daily mean pressure and reanalysis GPH is high, with a Pearson correlation coefficient of 0.99. Figure 7 shows air temperature and pressure in comparison with reanalysis temperature and GPH, respectively, for this period.

b. Wind

Prolonged readings of 0 wind speed or constant wind direction were deleted from the R.M. Young and Vaisala data for further analysis. It is assumed that these are faulty readings caused by icing of the sensor. Figure 8 shows a zoomed-in view

of the wind speed data from the 1994–96 period (R.M. Young sensor) and the 2003–04 period (Vaisala sensor). In a qualitative sense, it could be argued that the voltage output from the Makino sensor and the data from the R.M. Young sensor show coinciding peaks where the periods of record overlap in summer of 1994, but, because of the lack of metadata for the Makino records we do not attempt any further interpretation of this data. As mentioned previously, the Met One instrument was not calibrated for sufficiently high wind speeds, and recordings from this sensor during the 2002–03 season appear to be highly erratic as compared with the 2003–04 season. The maximum wind speed recorded by the R.M. Young instrument was 63.9 m s^{-1} on 15 February 1995. The Vaisala instrument

FIG. 7. AWS data for June 2003–June 2004: (a) Station data as recorded by the datalogger (dashed line), daily means (solid black line), and reanalysis as in Fig. 6. (b) Air pressure as recorded by the AWS and hourly reanalysis geopotential height at the 500-hPa level.

FIG. 8. Zoomed in view of the (a) 1994–96 wind speed data recorded by the R.M. Young anemometer and the 2003–04 wind (b) speed and (c) direction data recorded by the Vaisala anemometer. AWS data are 30-min wind speed samples. Hourly reanalysis wind speed and direction at the 500-hPa level (black) are plotted alongside station data for comparison. The critical wind speed (26.5 m s^{-1}) is shown as red line.

recorded wind speeds of over 40 m s^{-1} on several occasions during the 2003–04 season.

Since wind speed was sampled at 30-min intervals rather than averaged, statistical interpretation and comparison with hourly mean reanalysis wind speed is complex. The correlation between measured wind speeds and reanalysis is significantly lower than for temperature and pressure parameters. In qualitative terms, peaks in the measured wind speed do tend to coincide with peaks in the reanalysis, particularly during the 2004 spring season, and the range of magnitude found in the reanalysis data is comparable to that of the measured values.

Wind direction as recorded during the 2003–04 season by the Vaisala instrument shows that the wind primarily blows from the west or east on Denali Pass (Fig. 9). In contrast, reanalysis data indicate that the dominant wind direction in the free atmosphere at 500 hPa is broadly southerly, with seasonal shifts from southwest to southeast (Fig. 8; Hartl et al. 2020a). Given the location of the AWS on a pronounced, west–east-oriented saddle between higher terrain to the north and south, topography can be expected to strongly affect local wind speed and direction. Although there is some uncertainty associated with these data (e.g., because of unknown amounts of turbulence around the tripod stand), the dominance of west and east wind in the AWS records supports the idea that the pass acts as a wind funnel (Fig. 1).

McIlveen (2002) considers a drag force of 72 N as the critical threshold above which wind becomes dangerous to people, who may be blown over in such conditions. Following the method detailed in McIlveen (2002)—using the constants and approximations given therein, together with Denali Pass pressure and temperature data for the time periods when both are available—we find that on average the wind speed required to

generate a drag force of 72 N on Denali Pass is 26.5 m s^{-1} (minimum 25.9 and maximum 27 m s^{-1}). The 30-min sample wind speeds recorded by the R.M. Young instrument reached values at or above the critical wind threshold of 26.5 m s^{-1} in 654 cases. The corresponding hourly reanalysis wind speed is 27.4 m s^{-1} on average (standard deviation 6.7 m s^{-1}) and above 31.3 m s^{-1} in 75% of the cases. The minimum reanalysis wind speed for an occurrence of measured wind speeds above the threshold is 10.4 m s^{-1} . Dividing the AWS wind speeds above 26.5 m s^{-1} by the corresponding reanalysis data yields an approximation of a gust factor that decreases with increasing wind speed, roughly in the shape of a quadratic. Although this general relationship of gust factor to wind speed is concurrent with studies of gusts in complex terrain (e.g., [Ágústsson and Ólafsson 2004](#); [Naaim-Bouvet et al. 2011](#)), suggesting that the 30-min samples tended to capture gusts, a “true” gust factor for the summit region of Denali cannot be determined without further in situ data of both mean wind speeds and standard gust measurements, preferably at multiple sites on the mountain.

The Denali Pass AWS was installed as a response to the fatal accident of the JAC party in 1989, as discussed in [section 1](#). As detailed above, wind speeds clearly reach dangerous values frequently at Denali Pass. To showcase the meteorological developments leading up to and during the storm that resulted in the accident of the Japanese party, reanalysis data from 19 to 27 February 1989 are presented in Fig. 10. Synoptically, Denali was situated between a pronounced trough to the west and ridging in the Gulf of Alaska, in a strong southwesterly flow—a common wintertime pattern in the region (Hartl et al. 2020a). On 19 February, when the JAC team ascended to high camp, conditions were relatively calm. Wind speed noticeably picked up in

FIG. 9. Wind rose visualization of wind speed and direction during the 2003–04 period as recorded by the Vaisala anemometer.

the morning of 21 February, nearing the 26.5 m s^{-1} threshold for dangerous winds, before decreasing again slightly on 22 February. On the afternoon of 23 February, the wind increased again markedly, exceeding the threshold. After a brief lull during the night, winds rapidly increased again, reaching extreme values of around 50 m s^{-1} on 26 February. Wind direction shifted from south-southwesterly to westerly directions throughout the course of the storm. The strong westerly component may have led to increased terrain-induced funneling effects on Denali Pass, and the JAC team undoubtedly experienced very hazardous wind speeds. Aside from the primary danger of being physically blown over and a subsequent climbing fall in exposed terrain, any injury or equipment failure induced by a fall would have quickly become life threatening because of the very low temperatures. Wind chill equivalent (WCT) temperature dropped below -50°C on 23 February and remained below -30°C throughout the week. Facial frostbite time (FFT) was in the range of 5 min to instantaneous for the majority of the storm. We refer to [Moore and Semple \(2011\)](#) for definitions of WCT and FFT.

5. Discussion

The station location on Denali Pass was chosen by the JAC team with the aim of capturing the extreme wind speeds that are thought to have contributed to the fatal accident of the

Japanese mountaineers in 1989. Accurately measuring wind speed at Denali Pass is very challenging because of the harsh environment and very high wind speeds. All attempts to do so with cup anemometers in the early years of the station history did not prove sustainable. The anemometers experienced failures from icing and/or were torn off the station, hit by windblown pieces of rock, or otherwise mechanically destroyed. Expectations with regard to maximum wind speeds at the station location were exceeded and turned out to be higher than the initial calibration range of the ultrasonic sensor installed in 2002. All wind instrumentation experienced problems from icing on the sensors.

There is significant uncertainty associated with the temperature records from the Denali Pass AWS, as detailed in the previous sections. An uncertainty of $\pm 3^{\circ}\text{C}$ should be taken into account for temperature records beginning in 1992. The uncertainty of the temperature data during the first year of measurements is not quantifiable but assumed to be higher. While the nonstandard housing of the sensors at the Denali Pass AWS certainly introduced additional uncertainty and bias, shortwave radiation alone is known to cause significant biases in temperature readings from high elevation, unventilated sensors, especially over highly reflective snow surfaces: A positive bias of 1.3°C was found in records from a temperature sensor housed in a standard radiation shield above a glacier

FIG. 10. Overview of conditions 19–27 Feb 1989, reanalysis at 500 hPa: (a) Wind speed. The red line represents the threshold value for dangerous wind speeds (26.5 m s^{-1}). (b) Wind direction. (c) Air temperature at the 500-hPa level (solid black line), air temperature corrected with a regression factor (dashed black line), WCT (dotted black line), and FFT (blue line) as defined in Moore and Semple (2011). Negative FFT was set to 0. (d) GPH at 0000 UTC 26 Feb 1989. The red triangle denotes the location of Denali.

surface in Peru (Georges and Kaser 2002). Positive biases, especially during sunny, light-wind conditions, are also noted at the recently installed high-elevation station on Mount Everest (Matthews et al. 2020). Despite these caveats, we believe that the Denali Pass temperature data are a valuable and unique record of meteorological conditions in Denali's summit region. The comparison of AWS data and 500-hPa reanalysis air temperature data indicates that reanalysis captures much of the observed temperature range and variability and can serve as a first-order proxy for on-mountain conditions, confirming similar findings from Mount Everest (Moore and Semple 2004; Xie et al. 2008).

Since the end of the Denali Pass weather station project, significant technological advancements have been made in terms of instruments that can withstand extreme conditions, as well as data transmission and communication systems (e.g., Matthews et al. 2020). A weather station with real-time data in the upper elevations of Denali would likely improve the safety of climbers, would aid NPS operations, and could be used to verify and improve local weather forecasts. In the future, it would be highly desirable to extend the NPS station network on Denali to high camp (5242 m MSL)—a less exposed and more easily accessible location than Denali Pass that might allow for more reliable station operation. It would be key to integrate any new station in the summit region of Denali into the NPS network, not least for practical reasons (logistics and air support). In their report on the recently installed AWS network on Mount Everest, Matthews et al. (2020) note that support from the local climbing community is critical to ensure the longevity and continued maintenance of the stations. On Denali, collaboration with the NPS—which manages the

climbing activity on the mountain—is crucial for the same reasons.

On a more general note, the Denali Pass AWS project serves to highlight the importance of systematic metadata documentation and data management based on file formats that are cross-platform compatible and not dependent on proprietary software that may become obsolete in the future. These issues notwithstanding, the Denali Pass AWS also exemplifies that the initiative of one or several individuals can lead to significant achievements in terms of meteorological data collection and the great value of citizen science. For several years, the Denali Pass AWS was the highest weather station in the Americas and to this day there are very few continuous records from higher elevations. This hugely significant achievement cannot be overstated.

6. Conclusions

Maintaining a weather station in a location as high and exposed to extremely harsh conditions as Denali Pass is exceedingly difficult. Because of the efforts of Mr. Okura, the Japanese Alpine Club, and IARC, data were nonetheless collected during 17 years. Despite repeated equipment failures and variable data quality, the Denali Pass weather station project provides valuable insights into meteorological conditions at high altitudes on Denali—of relevance both from a meteorological point of view and for climbers hoping to summit Denali—and will, we hope, serve as a basis for future data collection efforts on the mountain.

Okura's goal was to prove that the summit region of Denali is subject to extreme wind speeds that can endanger climbers.

He achieved this goal with Denali Pass AWS project: Wind speeds in excess of 60 m s^{-1} were recorded at Denali Pass. People may be blown off their feet by significantly less extreme winds. Okura remains convinced that gale force winds were a main contributing factor in the fatal accident of his climbing partners. In situ observations—ideally accessible in real time—are vital for the safety of climbers and accident prevention and improve the potential for dedicated numerical forecasting of mountain weather on Denali.

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Data availability statement. The processed temperature time series, wind data for the 1994–96 and 2003–04 periods, and pressure data for 2003–04 are available for download at the data repository “pangaea.de” (Hartl et al. 2020b).

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