ANTARCTIC AUTOMATIC WEATHER STATION PROGRAM

30 Years of Polar Observations

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A quest for automated meteorological observations in the Antarctic leads to a continent-wide network of automatic weather stations supporting research and forecasting.

FIG. 1. A map of the Antarctic continent showing key geographical locations.

THE QUEST FOR AN AUTONOMOUS WEATHER STATION (1950s AND 1960s). Obtaining weather observations has been an important part of scientific discovery since the early days of exploration in the Antarctic. Understanding Antarctica's weather was one of the primary objectives of the International Geophysical Year (IGY) of 1957/58 and led to continuous observations of the Antarctic. The Antarctic continent covers an area roughly 1.5 times the size of the continental United States, over 14 million square kilometers (Fig. 1); but with approximately 50 staffed stations established by the end of the IGY (Summerhayes 2008), there was a need for observing ►

weather at remote locations beyond coastal areas and the peninsula area where main stations are located.

One of the first attempts at developing an automatic weather station (AWS) for the Antarctic was called a “Grasshopper” AWS, also known as the XG-1, installed near McMurdo Station during the Deep Freeze II field season (1956/57) (U.S. Navy 1965). By the early to mid-1960s, two additional portable automatic weather stations (PAWS) that could measure temperature, pressure, wind speed, and wind direction had been tested. One was known as the “Pinball” or XB-1 system and was battery powered, while the other system, XB-2, used two different power sources: batteries and nuclear power (U.S. Navy 1965). One XB-1 system, installed at Minna Bluff, failed after only a few weeks of operation. Another system was installed at Cape Hallett to the north of McMurdo Station and operated for approximately 5 months (M. Gibbs 2007, personal communication). Other XB-1 systems were likely installed during the mid to late 1960s. In the heart of the atomic age, one of the XB-2 PAWS was powered by a radioisotope thermoelectric generator (RTG) and designated XB-2N. The RTGs were built by Martin Marietta and specifically called System for Nuclear Auxiliary Power (SNAP-7C). The first XB-2N system was installed at Minna Bluff, just to the south of McMurdo Station, Antarctica, on 7 February 1962.

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THE FOUNDATION OF THE MODERN AUTOMATIC WEATHER STATION (1970s).

Recording Antarctic automatic weather station. The next step in the development of the modern Antarctic AWS occurred in 1974 with the installation of a recording AWS near Cordiner Peaks in West Antarctica (82.87°S, 53.20°W; Fig. 1). Installed by Austin Kovacs of the Cold Regions Research and Engineering Laboratory (CRREL), the station was manufactured by Rauchfuss Instruments (RIMCO), Ltd. and recorded temperature, pressure, wind run, and wind direction on a strip chart. This station only operated for 3 months. After recovery of the AWS 2 yr later, the strip charts were sent to Professor Werner Schwerdtfeger (see sidebar for additional information) of the Department of Meteorology at the University of Wisconsin—Madison (UW-Madison) for analysis. Professor Charles Stearns and his graduate student George Weidner were asked to digitize the strip charts because they had been doing this for strip charts from recording AWS units in Wisconsin. Stearns’s recommendation was to move to recording data on computer compatible paper tape to be punched by the AWS.

The Stanford AWS. At the same time the recording AWS was operating at the Cordiner Peaks, Stanford University’s Center for Radio Astronomy, under the direction of Dr. A. Peterson and Dr. M. Sites, with funding from the National Science Foundation (NSF), was developing a prototype AWS that would transmit data to the polar-orbiting *Nimbus-6* satellite. The initial deployment of this prototype AWS to Antarctica in 1975 was to test the cold weather capability of the electronics and the various sensors selected to measure temperature, air pressure, wind speed, and wind direction. Similar to the XB-2N PAWS of the 1960s, an RTG powered the prototype station.

This prototype Stanford AWS was initially deployed at the South Pole in February 1975. In December 1975, the AWS was moved to McMurdo Station and then moved to Marble Point in January 1976. It operated there until May 1977. With the somewhat successful operation of the prototype, the Center for Radar Astronomy at Stanford University was awarded a grant from NSF in December 1977 for the manufacture of six additional AWS, which were deployed during the 1978/79 field season in the area around McMurdo Station and at Byrd Surface Camp. Sensors on this version of the AWS consisted of a Weed platinum resistance thermometer (PRT) for external and internal temperatures, a Paroscientific Model 215A barometer for pressure, and the Bendix Aerovane Model 120 for the wind speed and wind direction.

One AWS was equipped to measure humidity using a Vaisala HMP-14U humidity probe. Renard and Salinas (1977) give an analysis of this AWS.

The Argos satellite system was developed in 1978 by the Centre National d'Etudes Spatiales (CNES), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA) (see www.argos-system.org) to facilitate the transfer of meteorological and oceanographic data around the world. The Argos capabilities were a large improvement over the data transfer system used by the initial Stanford prototype AWS, so the AWSs were redesigned by Stanford to transmit data via the Argos system on the Television and Infrared Observation Satellite series N (TIROS-N)/NOAA series of satellites. The data were transmitted once every 200 s.

During the 1979/80 Antarctic field season, the Nimbus AWSs were converted to the Argos-based

AWSs, and additional AWS units were deployed by Stanford personnel, including one at Dome C. Four of the units were to be installed along a traverse route between Dumont D'Urville and Dome C and would use batteries instead of the RTG. By the end of the field season, only two of the four had been installed at sites along the Adélie Coast, D-10 and D-17. Only the Argos AWS units installed at Byrd, Dome C, and Marble Point operated through the 1980 austral winter.

ANTARCTIC AWS PROGRAM AT UW-MADISON (1980–2010).

1980s. Given the many frustrations associated with attempting to work in the Antarctic, it is perhaps understandable that, after designing a pioneering AWS, Stanford sought to transfer maintenance of the AWS network to another entity. In 1979, Stearns submitted a proposal to NSF that transferred the Antarctic AWS program

DR. CHARLES R. STEARNS' ROLE IN THE DEVELOPMENT OF THE AWS NETWORK

In the late 1970s, Professor Werner Schwerdtfeger, an avid Antarctic researcher, introduced the Antarctic to a colleague at UW-Madison, Professor Charles Stearns (Fig. SBI). Stearns was already very active in developing and setting up instrumentation for meteorological experiments in Wisconsin and other locations. Schwerdtfeger asked his colleague to help in the digitization of the strip chart recorded in Antarctica at Cordiner AWS site given Prof. Stearns's existing expertise with strip chart digitization. This request ultimately led Stearns to become the steward of the USAP AWS network.

Stearns's experience and efforts with AWS systems led to the expansion of weather stations around the Antarctic. He often devised creative solutions to the challenges in maintaining the network. For example, once an AWS site was installed on the ice shelf, it became a challenge to get back to the site in subsequent seasons. Spotting a 3-m tower from a helicopter was problematic even in good weather. With helicopter time limited for each science project, Stearns decided to install beacon transmitters on the ice shelf AWS units that could be picked up by the direction-finding capability of the navy's UH-1N Huey helicopters.

Stearns was ahead of his time with his open data-sharing policy. Long before it was a standard practice, he freely shared his AWS observations, often in real time. Seeing so many other scientists benefit from the observations made by the network was a great satisfaction for Stearns.

In 1982, Stearns was awarded the Antarctic Service Medal by the National Science Foundation for his scientific achievement under the USAP. His commitment to the community was seen in his service to the AMS as he served on the AMS Committee on Polar Meteorology and Oceanography from 1986 to 1988, and was program chair of the Second Conference on Polar Meteorology and Oceanography. Stearns served on the NSF Committee on Antarctic Operations and Engineering from 1996 to 2003. He was elected a fellow of the AMS in 2004. On 12 July 2010, he was posthumously awarded the Goldthwait Polar Medal at the Fifth Antarctic Meteorological Observation, Modeling, and Forecasting Workshop in Columbus, Ohio.

Stearns's vision was critical to the evolution of the modern-day AWS network as it exists in Antarctica because he was the principal investigator of the project from 1980

FIG SBI. Professor Charles R. Stearns (1925–2010).

to 2008, his longest-running project. He deployed to Antarctica for 18 field seasons. This program oversaw the first large-scale meteorological instrumentation of the Antarctic continent in history. Always aware of the challenges of doing science in this physically demanding environment, he was often fond of saying "Mother Nature always bats last." Stearns passed away in June 2010, and this paper is dedicated to his memory and the legacy he has left for Antarctic meteorology.

FIG. 2. The seeds of the Antarctic AWS network in 1980 began with two stations near McMurdo Station and Ross Island, along with stations at Byrd, Dome C, and the Adélie Land coast.

from Stanford University to UW-Madison. Stanford agreed to provide support in the form of modifying four AWS units to be deployed by the British Antarctic Survey (BAS) in the Antarctic Peninsula and preparing five units for the McMurdo area. The grant, awarded in 1980, gave the UW-Madison personnel, in consultation with Stanford, the opportunity to gain a working knowledge of the AWS and valuable experience in the field as additional stations were installed around McMurdo by Stearns and Mike Savage (Fig. 2). By the summer of 1982, Stearns and Savage along with the BAS had installed 13 units.

The end of the Stanford involvement with the Antarctic AWS program led Stearns to add additional personnel to assist with station maintenance and fieldwork. Weidner formally joined the AWS program to begin the conversion of the electronics from RTG-powered units to battery-powered units and to help Stearns with fieldwork (Fig. 3). The additional personnel allowed Savage to undertake a 6-week traverse with the French team to install the AWS in Adélie Land, which completed the line from Dumont D'Urville to Dome C. These new battery-powered AWS units were called the Wisconsin 2A AWS because the original Nimbus-based units were referred to as AWS 1, followed by its Argos-based redesign to AWS 2.

Shortly after being deployed, problems began to develop with the units installed on the Antarctic Peninsula. Technicians at Rothera Station examined the two AWS units that failed to work in the field and found that the printed circuit (PC) boards

FIG. 3. Jimmy AWS (with Prof. Stearns), located on Star Glacier at Arrival Heights above McMurdo Station, is an example of a battery-powered Stanford/Wisconsin 2A AWS station. These stations have the characteristically large electronics enclosure (as compared to Wisconsin 2B and newer AWS), cylindrical Argos antenna, and noncentered aerovane. (Courtesy Mike Savage.)

were suffering from corrosion. Examination of the malfunctioning AWS back at UW-Madison led to the conclusion that a new AWS should be designed, new PC boards should be fabricated, and new software should be written for the AWS. The new AWS was designated the 2B version. The Space Science and Engineering Center (SSEC) at the UW-Madison modified the AWS design in 1983, and new PC boards were fabricated. The central processing unit (CPU) boards only had a few modifications, whereas the interface boards underwent a major redesign, providing a much simpler layout than for the Wisconsin 2A AWS. At the same time the AWS hardware was being redesigned, the AWS's operating software was rewritten in order to accommodate new sensors (humidity and vertical temperature difference) and to better pack the data transmission with as much data as possible. In addition, a simple dipole antenna was fabricated to replace the commercial tubular antennae, which were failing because of the effect of the cold, dry conditions on the glue that held the connecting PC board in place. Also, the temperature shields were grounded to the sensor boom as high static voltage was building up on the radiation shields of the Weed temperature probe that resulted in damaged components on the CPU board.

The newly fabricated Wisconsin 2B stations were deployed in the 1983/84 through 1985/86 field seasons (Figs. 4, 5). Some were placed along 80°S from the Transantarctic Mountains to the middle of the Ross Ice Shelf. One was placed at the ice edge at 180° longitude, and three sites were established in the southern part of the Ross Ice Shelf and near the top of the Beardmore Glacier. Three other AWSs were installed in an array with one site near the South Pole Amundsen–Scott station and two sites some 20 km out from the station. Deployment of AWS at various locations around the continent was driven by both science objectives of the AWS project and individual external science projects.

The late 1980s saw three additional developments in the AWS's configuration. The first was the removal of all of the RTG-powered units, which were replaced with AWS powered by batteries. This was done to conform to the nuclear-free designation for Antarctica. The last RTG was removed from Dome C in 1995. Traditional AWS units were placed on Buckle Island in early 1987 and on Scott Island in late 1987. A return visit showed that the stations needed more protection from the salt spray and ice. As a result, the “doghouse” AWS was designed. This type of AWS was enclosed in a wooden structure similar in shape

to a doghouse and only measured air temperature and pressure. Icebreaker trips along the Adélie Land coast and northern Victoria Land allowed doghouse AWS to be deployed on the Balleny Islands and Scott Island on the way to McMurdo during icebreaking duties. Eventually, doghouse AWSs were also installed at Young Island and Possession Island. Today, only the Possession Island doghouse AWS continues to operate, although only in the summer due to a failing power system. The last modification to the AWS 2B

FIG. 4. Schematic diagram of the Wisconsin 2B AWS system shows the components of the base system. Additional components were added, including ADG, water temperature, and snow temperature.

FIG. 5. Pegasus North AWS located on the approach to the Pegasus skiway (near McMurdo Station) is an example of a Wisconsin 2B AWS. This is the only year-round observing system at Pegasus. The chains are used to prevent the AWS tower from being toppled during high wind events.

FIG. 6. The distribution of AWS sites, as seen in the map circa 1990, reveals the cluster of AWS observations on the Ross Ice Shelf and the Antarctic Peninsula, with a few stations on the Adélie Land coast and the Polar Plateau.

FIG. 7. By 2000, the Wisconsin AWS network covers several sectors of the Antarctic continent.

was the design of an additional PC board that allowed for 16 differential input channels. These were used on AWS units intended for measuring snow temperature profiles down to depths of 8–16 m, in support of glaciological and surface energy budget studies.

1990s. The AWS network continued to expand during the 1990s in support of a variety of specific research projects (Fig. 6). In order to study the katabatic flow down around Terra Nova Bay, several units were installed on the Reeves Glacier. AWSs were also installed at historic sites along the Adélie Land coast at Port Martin and Cape Denison. In one of the more unique locations, an AWS was installed at the top of Mount Erebus. The first inland AWS units in the western sector of the East Antarctic Plateau were installed by the Japanese Antarctic Research Expedition (JARE) at Relay Station and Dome Fuji, one of the highest Antarctic elevations that has been tried for an AWS.

Also during this period, a new AWS configuration was designed for stations to measure water temperature at AWS sites on the west side of the Antarctic Peninsula in support of the Long Term Ecological Research (LTER) project (Baker and Stammerjohn 1995). Unfortunately, the first design had to be redone because the close proximity of the AWS to the saltwater caused considerable internal corrosion, and the stations only worked intermittently.

By the mid-1990s, the network of AWS had expanded to cover locations along the Adélie Land coast, Reeves Glacier, islands off Cape Adare and West Antarctica, the Balleny Islands, the Ross Ice Shelf, inland West Antarctica and the Siple Coast, the Antarctic Peninsula, and the high Polar Plateau.

Collaborative assistance in the installation and maintenance of remote AWS from the British, French, Italian, and Japanese national Antarctic programs made this possible. By 1995, the Wisconsin AWS network had 50 units installed across the Antarctic continent.

The basic AWS unit had progressed through several versions and manufacturers of instruments up to this time (see Table 1). Paroscientific barometers remained the primary instrument for pressure although some barometers from Vaisala were used. Wind speed and direction measurements started with the Belfort/Bendix anemometers and gradually changed over to the R. M. Young anemometers with Taylor high wind speed systems to augment or replace anemometers where strong katabatic winds were observed, such as along the Adélie Land coast. Temperature measurements were made with a Weed 1000-ohm PRT. The temperature difference between 3 and 0.5 m was measured using either a thermocouple or Weed thermometers. Several stations such as Siple Dome, Pegasus South, and later Kominko–Slade AWS also had snow temperature profile measurement capabilities, which again used thermocouples with Weed thermometers. Finally, relative humidity was measured with Vaisala HMP-31UT, HMP-35, and then HMP-45 sensors (see Table 1).

2000s. As the year 2000 approached, several factors led to the realization that a new AWS system needed to be designed. One of the main factors was that critical components were no longer available because the design was 20 yr old. Advances in technology were also a factor because a newly designed station could have reduced power requirements, greatly reduced component size, more processing power, and the ability to add more and different sensors. The new unit had to be capable of transmitting data via an Argos-certified platform terminal transmitter or other communications methods such as radio modem or Iridium satellite phone. The choice was between building a newly designed station in house or using a commercial off-the-shelf (COTS) data logging system. Part of the difficulty in making this decision was that at this time commercial products were not built to the required specifications suitable for polar use and thus were not likely to function on the high Polar Plateau, where temperatures can become as cold as -80°C (the world record temperature is -89.2°C recorded at Vostok Station, Antarctica).

In 2001, the Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) program received last-minute AWS support to aid its field studies. Two AWS units were to be deployed on Kirkwood and Dismal Islands in Marguerite Bay.

Because of the short lead time, these installations were the first to incorporate the Campbell Scientific Inc. (CSI) CR10X data loggers as the core of the AWS.

Early 2000 also saw the calving and breakup of large icebergs off the Ross Ice Shelf (Lazzara et al. 1999). As the icebergs moved to the west and closer to McMurdo, a plan was conceived by Professor Doug MacAyeal of the University of Chicago to put AWS/global positioning system (GPS) stations on some of the bigger icebergs as a floating observation system, for ocean currents as well as weather in the Ross Sea (Sergienko et al. 2007; MacAyeal et al. 2008). Three stations were installed on B-15A in January 2001. Other stations were installed on C-16 (2001), B-15K (2003), B-15J (2003), Nascent (Ross Ice Shelf edge, 2004), and Fountain (Drygalski Ice Tongue, 2005). These later installations also utilized the CSI CR10X. By the end of the 2000/01 field season, over 55 UW stations were installed in the Antarctic (Fig. 7).

By 2005, the AWS program was ready to move to the CR10X-based electronics as a standard AWS unit. The first installation was at the base of Mulock Glacier (Mary AWS), with additional CR10X-based AWSs installed at Windless Bight, Ferrell, and Willie Field (Fig. 8). In addition, acoustic depth gauge

Fig. 8. Windless Bight AWS, tucked into Ross Island on the McMurdo Ice Shelf, is a CR10X Wisconsin AWS.

(ADG) sensors were added to these stations to begin a study of snow accumulation (Knuth et al. 2010). In 2007, the BAS decided to upgrade the five stations that they were servicing for the UW-Madison AWS program to CSI CR1000 (successor to the CR10X) electronics. By the 2008/09 field season, the AWS program also had begun replacing both Wisconsin 2B and CR10X electronics for the newer CR1000-based AWS (Fig. 9). This process is continuing today as rapidly as practical with a priority given to sites where there is a requirement for more and better sensors that require the updated electronics to support them. By 2011, roughly 60 sites remained in the UW-Madison AWS network (Fig. 10), over half of all long-term AWS units operating in the Antarctic (see supplemental Table ES1 online at <http://dx.doi.org/10.1175/BAMS-D-11-00015.2> for the list of UW-Madison AWS over the entire project).

The instruments on the AWS units have changed and expanded during this decade (Fig. 11 and Table 1). Pressure measurements continue to use the very dependable Paroscientific Digiquartz barometers. The installation of Vaisala barometers in a few locations have proven to be quite reliable over the years, whereas experiments with other pressure sensors proved unsuccessful. Temperature measurements are now made with the R. M.

TABLE 1. AWS specifications and manufacturer websites/contact information.					
Sensor	Years in use	Accuracy over -60° to 20°C	System resolution	System accuracy	Notes
Temperature					
Weed 1000-ohm PRT	1978–present	$\pm 0.25^{\circ}\text{C}$	0.125°C	$\pm 0.5^{\circ}\text{C}$	Less than 10 probe failures over 30 yr
http://ultra-nspi.com/product_groups/industrial/rtd_pdfs/RTD-201_203.pdf					
CSI RTD 100-ohm PRT	1999–present	$\pm 0.3^{\circ}\text{C}$ at 0.0°C	0.01°C	$\pm 0.5^{\circ}\text{C}$	Used with CRI10- and CRI1000-based AWS, no failures observed
www.campbellsci.com/documents/manuals/rtd.pdf					
Nominal temperature difference 4.0–0.5-m copper constantan thermocouple wire	1984–present	$\pm 0.2^{\circ}\text{C}$ over temperature range	0.0625°C	$\pm 0.125^{\circ}\text{C}$	Calibrated for 0.0°C difference in ice bath; new AWS use two PRTs
Homebuilt					
Pressure					
Paroscientific Model 215A	1978–present	$\pm 0.08\text{ hPa}$ less than $\pm 0.1\text{ hPa yr}^{-1}$	0.04 hPa	$\pm 0.1\text{ hPa}$	Less than five gauges failed—long-term drift typically 2–4 hPa over 25 yr for early models; latest generation 1–2-hPa lifetime drift
www.paroscientific.com/pdf/2000.pdf					
CSI 105/PTB101	1999–present	$\pm 3.0\text{ hPa}$ $\pm 0.1\text{ hPa yr}^{-1}$	0.1 hPa	$\pm 3.0\text{ hPa}$	Used in less extreme temperature locations
www.campbellsci.com/documents/product-brochures/b_cs105.pdf					
CSI 106/PTB110	2007–present	$\pm 1.5\text{ hPa}$ $\pm 0.1\text{ hPa yr}^{-1}$	0.1 hPa	$\pm 1.5\text{ hPa}$	Used in less temperature extreme locations
www.campbellsci.com/documents/product-brochures/b_cs106.pdf					
Humidity					
Vaisala HMP14UT	1979–83	$\pm 4\%$	0.04%	$\pm 4\%$	Used in one early prototype AWS2 station

Vaisala HMP31UT	1984–2005	±2% 0%–90% ±5% 90%–100%	0.04%	±2% above –20°C	AWS needed to provide regulated voltage
Vaisala HMP35A/D	1989–2010	±2% 0%–90% ±5% 90%–100%	0.04%	±2% above –20°C	HMP35A provided regulated power
Vaisala HMP45A/D	1997–present	±2% 0%–90% ±3% 90%–100%	0.04%	±2% above –40°C	Improved sensor using less power
www.ambimet.cl/documentos/ambimet-sensor-hmp45a.pdf					
Vaisala HMP155	2007–present	±2.5% 0%–90% ±2.5% 90%–100%	0.04%	±2% above –40°C ±5% –40° to –60°C	Improved sensor with lower temperature operation
www.vaisala.com/Vaisala%20Documents/Brochures%20and%20Datasheets/HMP155-Datasheet-B210752EN-D-LOW-v4.pdf					
Wind					
Bendix Model 120 Aerovane	1978–present	±1% of wind speed threshold 1.0 m s ⁻¹ ±2° for direction	0.250 m s ⁻¹ 1.5° for direction	±1% wind speed ±3° for direction	Bendix sold Aerovane to Belfort
Belfort Model 122/123	1984–present	±1% of wind speed threshold 0.9 m s ⁻¹ ±2° for direction	0.250 m s ⁻¹ 1.5° for direction	±1% wind speed ±3° for direction	Belfort models had frequent problems and new ones were not purchased after 1992
www.belfortinstrument.com/content/wind_m5_122.cfm					
R. M. Young Model 05103/106	1990–present	±0.3 m s ⁻¹ or 1% of reading ±3° for direction	0.2 m s ⁻¹ 1.5° for direc- tion	±1% for direction ±3° for direction	Currently standard wind sensor used
www.campbellsci.com/documents/manuals/05103.pdf					
Taylor Model 201 High Wind System	1989–present		0.33 m s ⁻¹ 1.5° for direction	±2% for direction ±3° for direction	Used at sites with extreme winds
No website information available					
Snow accumulation					
Campbell Scientific SR50(A)	2005–present	±0.4% of distance to snow surface	0.25 mm	±1.0 cm (assumes ideal flat surface)	Measurements depend on surface conditions (sastrugi, blowing snow, etc.)
www.campbellsci.com/documents/manuals/sr50.pdf					
www.campbellsci.com/sr50a					
Radiation					
Campbell Scientific (various types)	2008–present				Establishing reliability
www.campbellsci.com/documents/product-brochures/b_cnr4.pdf					
www.campbellsci.com/documents/manuals/cnr2.pdf					
www.campbellsci.com/documents/manuals/li200x.pdf

FIG. 9. Sabrina AWS, located on the Ross Ice Shelf, is a prototype CRI000-Wisconsin AWS. (Courtesy Shelley Knuth.)

Young resistance temperature detector (RTD) thermometer along with the in-house fabricated Weed PRT. R. M. Young and Taylor wind systems remain the standard wind monitoring sensors. The upper and lower temperature measurements use RTD thermometers instead of thermocouples, and most of the snow temperature profile measurements have been terminated. The relative humidity measurements now use the Vaisala HMP45 instrument but will gradually be replaced with the Vaisala HMP155 instrument because it is specified to operate at temperatures down to -80°C . Additional instruments are being added to increase the capabilities on the redesigned stations. The ADG is becoming a standard addition instead of a specialized instrument for a few stations. The newest AWS sensors are pyranometers and net radiometers, which will become standard as the stations are upgraded or replaced (Table 1).

AWS DEPLOYMENT AND SERVICING. With roughly half of all Antarctic AWS sites belonging to the UW-Madison AWS network, it represents the largest network in terms

of number of sites and area covered. Maintenance of this network requires a significant effort. Yearly deployments to the Antarctic are required to service existing AWS systems, install new ones, and remove units that are no longer necessary. Only two to five team members visit the Antarctic each year to service and deploy UW-Madison AWSs.

It cannot be emphasized enough that doing fieldwork in Antarctica can be a challenging, frustrating, and occasionally dangerous experience. Given the potential for conditions to very quickly change from clear, calm, and benign to life threatening cloudy, foggy, or windy with white out conditions, safety is of the utmost concern when visiting the AWS sites. Multiple transportation modes are employed to get to the AWS sites. Near large stations and summer field camps, snowmobiles, trucks, and tracked vehicles are used to get to nearby AWS sites. Helicopters are also employed for visiting AWS sites within 100 km of main stations, ships, and helicopter summer camps. Ships with zodiacs (small inflatable, portable boats) have also serviced some AWS sites. However, fixed-wing aircraft have been the primary means of accessing much of the network. A majority of sites are reachable via ski-equipped Twin Otter aircraft, although historically some sites were installed with LC-130 aircraft. The pilots that fly to the AWSs are often asked to land at sites with no landmarks, rough surfaces, and challenging weather and do a remarkable job in transporting personnel and equipment to

FIG. 10. The 2010 AWS network map depicts the increased geographic coverage over the continent.

FIG. 11. A schematic diagram of the Wisconsin CRI000 AWS system depicts the variety of instrumentation on a base station.

these remote sites safely. Fortunately, there have been no significant accidents while servicing AWS, with only two rough landings over the life of the program.

AWS sites that are not installed on rock, especially those on ice shelves, are known to move (Turner et al. 2009). The installation of the Lorne AWS site near Ross Island was due to the northward trek of Ferrell AWS, which moves on the order of 0.7 km yr^{-1} to the north-northeast and has moved approximately 22 km

since being installed in 1980. This issue impacts the in situ monitoring of the local climatology and impacts maintaining a ring of sentinel AWS units near McMurdo Station for weather forecasting as in the case of Ferrell and Lorne AWS. Because of this and with a need for accurate station elevations in numerical models, efforts have been made to accurately measure the location and elevation of the AWS sites using modern GPS receiving equipment during site visits.

It is an important goal to routinely visit key AWS sites to properly maintain the AWS unit. However, over the 30 years of the Wisconsin AWS project, the U.S. Antarctic Program (USAP) has seen a dramatic increase in the number of science activities. As a result, the transportation options to remote field sites are often oversubscribed. Combined with limited funding for logistics and fuel, it is not possible to visit all AWS sites each season. Additional support from collaborating nations allows approximately a quarter to one-third of the AWS network to be visited during the field season. Yearly visits to all stations are ideal but are not realistic. The accumulation of snow at many of the sites, if not visited routinely, may cause the AWS to become buried. Keeping the sensors at a fixed height above the snow is always the objective but difficult to achieve in practice. The effect of the height of the sensors above the snow surface is only recently being studied with regard to temperature (Ma et al.

TABLE 2. Typical problems associated with AWS observations.

Temperature	Pressure	Wind	Relative humidity	Other
Passive or naturally ventilated radiation shield in low wind and high sunshine leading to erroneously high temperatures	High wind gust impacting measurements	Freezing up of anemometers covered in rime/frost	Failing of regulated power supply on probe	Anchoring for the AWS ablate away
	Tower vibration in high wind impacting measurements	Damaged impellers and anemometers in high winds	Damage to sensing element from salt deposits at maritime locations	Static buildup from blowing snow impacting data transmissions
	Blocked pressure port (mostly at maritime locations)	Bearing failing in some aerovanes	Failing of early model sensing elements at extremely cold temperatures	Antenna transmission drift or broken prongs
		Impeller nose pieces working loose in strong winds and icing conditions		Holes punched in solar panels from flying debris
		Potentiometer wearing prematurely and failing when the wind direction constancy was very high		

2011), and to date these corrections are not applied to the observations. In addition to mechanical sensor failure, Table 2 lists some of the challenges that the AWS sensors have experienced.

AWS DATA ACQUISITION AND DISSEMINATION. The official observations used to create the formal AWS archive come from the Argos satellite data collection system directly. Argos collects observations via a host of direct broadcast reception sites around the world as well as via recorded collections. Three means have been used over the life of the project to receive the data from Argos: round tapes, the Internet, and now monthly compact discs (CDs). Other communications methods have been tested (Iridium) or are currently being implemented (900-MHz radio modem).

Over the modern Antarctic AWS network era (1980–present), the real-time acquisition and relay of the observations via the Argos satellite system and subsequent relay via the Global Telecommunications System (GTS) has allowed forecasters in the field as well as researchers and numerical modeling centers to acquire the data. Roughly 31 AWSs in 2011 that formally have assigned identification numbers are made available to the GTS. Real-time acquisition from Argos also provides a secondary means for providing observations to the GTS and to users in real time in the Antarctic (via Internet distribution systems, e-mail, etc.). As a result, forecasters in the field are able to acquire the data within 2 h, and the observations are available for assimilation by real-time numerical weather prediction (NWP) systems. The near-real-time AWS observations are also available to the research community allowing for time-critical monitoring of weather data when required. Finally, this system provides a means for getting observations in real time to students as part of educational outreach conducted by the AWS project.

QUALITY CONTROL OF AWS OBSERVATIONS. The harsh conditions in Antarctica and the circuitous route from AWS to satellite to ground station almost guarantee that some spurious observations will appear in the AWS dataset. For the first decade with the focus on adapting the stations to be reliable in the inhospitable environment and expanding the network of stations to support scientific investigations, the only quality control (QC) performed was a gross error check of the data as they were decoded. This check consisted of a set of limits for each parameter, and if the observation was outside of those limits, then it was considered an error.

As the network matured in the second decade (1991–2000), more resources were available to QC the data. The 3-hourly dataset was visually scanned by hand, looking for any observation that was inconsistent with the prior or subsequent observations. After several years of quality control data were completed, it became obvious that there was a problem with the temperature observations in the summer months under light or no wind conditions. The temperature sensor would heat up, in spite of the radiation shield, because of direct and/or diffuse solar radiation. The QC procedures were adjusted to remove temperature spikes during low wind conditions (Genthon et al. 2011).

In an effort to expedite a rigorous QC while applying knowledge of typical errors encountered during manual QC efforts, Mark Seefeldt (in consultation with Linda Keller) developed a set of interactive QC programs using the Interactive Data Language (IDL) software. Each variable was examined separately and visualized as a time series of varying length from hours to an entire month. The mean and standard deviation were calculated for the observations in the user-selected time period. Three standard deviations from the mean in the user-selected time period were used to set the limits for rejecting an observation. Anything outside of these limits was marked as a possible error and highlighted in the time series. Once this was completed, a scientist could call up any variable and see what observations the program thought were in error in comparison to the rest of the time series. The interactive software then allows the scientist to keep observations that were felt to be correct and remove others that the automated QC program did not flag as being incorrect. All removed observations are saved in a separate file and are accessible. This manual intervention, while time consuming, allows a more careful determination of the appropriateness of the time series observations, especially during periods of high variability, such as a rapidly progressing extratropical cyclone or a pronounced diurnal cycle. The wind speed and direction are completely manually analyzed for this reason. Pressure is the slowest changing variable, making its quality control straightforward. Temperature is more challenging in the summer because of radiation effects. The variability of the relative humidity is more location dependent.

In addition to finding spurious observations, the IDL programs also allowed an expansion of the types of corrected datasets available. Since 2001, quality controlled datasets for 10-min, 1-h, and 3-h time periods have been made for each month and are available on the Antarctic Meteorological Research

Center (AMRC) FTP site (<ftp://amrc.ssec.wisc.edu/pub/aws/>) and on the AMRC Repository for Archiving and Managing and Accessing Diverse Data (RAMADDA) website (<http://amrc.ssec.wisc.edu/repository>).

SCIENCE APPLICATIONS USING AWS OBSERVATIONS. As discussed above, real-time use of data from the AWS network is critical for both forecasters and numerical weather prediction efforts, but the primary motivation for the AWS network is to support research activities. The following provides a limited overview of some research results that have used AWS observations. These results have mainly an atmospheric focus, although examples of research activities in other fields are also mentioned.

One of the initial motivations for the AWS network was to provide observations of the Antarctic climate across the range of climatic conditions found on the continent. Staffed observational sites tend to be located mainly along the coast with only a few interior sites. The AWS network helped “fill the gaps” in weather observations across the continent (Fig. 12). Stearns et al. (1993) presented one of the earliest climate studies based on observations from the first decade of the AWS network. Their work highlighted the fact that observations from coastal locations, where most staffed sites were located, are not representative of the broader Antarctic climate. Allison et al. (1993) used AWS data from the U.S., Australian, and French AWS networks to analyze the climate of East Antarctica, between 100° and 140°E. Some of their findings included the presence of a coreless winter temperature regime, maximum wind speeds just inland from the coast rather than at the coast, and high directional constancy of the winds with the wind direction becoming oriented more downslope during the winter months. They also noted that Dome C in the interior of the East Antarctic ice sheet had an absolute lowest minimum temperature of -84.6°C . More recently, Aristidi et al. (2005) analyzed two

decades of weather observations at Dome C to determine the suitability of this site for an astronomical observatory. Mean wind speeds at Dome C were found to be less than 3 m s^{-1} , the lightest wind speeds of all but one astronomical observatory site for which long-term weather observations were available. Aristidi et al. (2005) reiterated the results of Allison et al. (1993) and found a coreless winter, with nearly constant temperatures, that lasts for 6 months.

One issue that has plagued climate studies that use AWS data is missing values in the time series due to AWS failures. Shuman and Stearns (2001) combined satellite-retrieved surface temperatures with AWS observations to create continuous time series of surface air temperature at four AWS sites in West Antarctica and on the Ross Ice Shelf. They found warming at two sites and cooling at two sites over the 10–19-yr records. The warming of 2°C at Siple AWS over 19 yr was the only significant temperature trend. Reusch and Alley (2004) used artificial neural networks (ANNs) to fill gaps in AWS time series from six sites in West Antarctica and on the Ross Ice Shelf, creating a continuous 15-yr record for these sites. Based on this continuous time series it was found that three of the sites showed significant warming during this period.

Although the AWS network provides enhanced spatial coverage across the Antarctic continent, the density of weather observations is still less than for most other land areas. Steig et al. (2009) combined

FIG. 12. A map of known AWS shows the distribution of AWS as of 2011. The Wisconsin network includes all stations denoted with a triangle, regardless of color.

satellite-retrieved surface temperature and AWS-observed temperatures to determine the spatial variability of temperature across the Antarctic continent. This information was then used with 50-yr time series of temperature from staffed observation sites to evaluate temperature trends across the continent. They found significant warming trends for 1957–2006 across most of West Antarctica on annual and seasonal time scales, except for autumn, and warming across the continent of $0.12 \pm 0.07^\circ\text{C}$ per decade. More recent studies challenge this result (O'Donnell et al. 2011) and point to the continued need to observe surface meteorology and climatology with the AWS network.

Turner et al. (2004) describe efforts by the Scientific Committee on Antarctic Research (SCAR) to compile monthly and annual near-surface climate data from the Antarctic. This dataset, known as Reference Antarctic Data for Environmental Research (READER), provides a valuable and easily accessible record of Antarctic climate and relies heavily upon AWS observations to provide adequate spatial coverage. An indication of the increasing importance of AWS observations for climate studies is the use of AWS data in the annual *State of the Climate* reports

published by the American Meteorological Society (AMS). The 2009 report (Colwell et al. 2010) highlighted several AWS sites that observed record high temperatures during 2009, including Dome C II, which had a July mean temperature that was 7.5°C above the long-term mean.

Solomon and Stearns (1999) used AWS observations from the Ross Ice Shelf to place the weather conditions encountered by Robert Falcon Scott's South Pole party on their ill-fated return from the South Pole in a broader climatological context. Previously, the weather conditions reported by Scott's party were assumed to be typical for the Ross Ice Shelf in late February and early March. Solomon and Stearns (1999) showed that the conditions encountered by Scott and his men were $10^\circ\text{--}20^\circ\text{F}$ ($\sim 5^\circ\text{--}10^\circ\text{C}$) colder than has been observed by AWS since 1985, leading them to speculate that the unusually cold conditions encountered by Scott's party may have contributed to their deaths.

One of the main uses of the Antarctic AWS network has been to analyze the unique near-surface wind regime of the Antarctic continent. Wendler et al. (1993) used AWS observations from Adélie Land to document the details of the katabatic wind regime of this region. Wind speeds were found to increase from the interior (Dome C) to near the coast (AWS D-47, approximately 100 km inland) before decreasing slightly to the coast. The directional constancy (the ratio of the vector-mean wind speed to the scalar-mean wind speed) of the winds was found to exceed 0.9 for most months and most locations in Adélie Land, with notably lower directional constancy at Dome C. Parish et al. (1993) used a two-dimensional mesoscale model to simulate the diurnal evolution of katabatic winds in Adélie Land. Their simulations revealed the persistent katabatic forcing present in this region, except during midsummer, when solar heating disrupts the katabatic drainage. Their results were consistent with AWS observations and helped explain the high directional constancy found by Wendler et al. (1993). Early Antarctic explorers (Mawson 1915) noted the exceptionally strong and persistent winds near the Adélie Land coast at Cape Denison, including a monthly-mean wind speed in excess of 29 m s^{-1} and an annual-mean wind speed of 19.1 m s^{-1} . Wendler et al. (1997) used AWS observations from Cape Denison and Port Martin to verify the exceptional winds reported by Mawson and found that current AWS observations are consistent with the exceptional wind regime described by Mawson. Bromwich et al. (1993) used two years of AWS observations near Terra Nova Bay, Antarctica, to document

FIG. 13. Wind rose plots for strong katabatic events during austral autumn 2005 for the Ross Ice Shelf region. The length of the petal indicates frequency of each direction. Each circle around the center indicates a frequency increment of 5%. For example, the wind rose for Gill AWS (GIL) has westerly winds approximately 28% of the time, with 22% westerly at $2.0\text{--}5.9\text{ m s}^{-1}$, 5% westerly at $6.0\text{--}9.9\text{ m s}^{-1}$, and 1% westerly at greater than 10.0 m s^{-1} (from Seefeldt et al. 2007).

the confluence of katabatic drainage on the Antarctic Plateau above Reeves glacier and the resulting intense katabatic winds at the mouth of the glacier at Terra Nova Bay.

Carrasco and Bromwich (1993) used infrared satellite images and AWS observations to document the propagation of katabatic winds across the Ross Ice Shelf for distances of up to 1,000 km. Since this initial work, the Antarctic meteorological community has worked to understand the mechanisms responsible for these features. Seefeldt et al. (2007) employed the extensive network of AWS units on the Ross Ice Shelf to document the dominant wind regimes over the Ross Ice Shelf. These wind regimes included strong and weak katabatic drainage, barrier winds, and light winds (Fig. 13). Steinhoff et al. (2009) combined AWS and satellite observations with forecasts from the Antarctic Mesoscale Prediction System (AMPS) (Powers et al. 2003) to study a single event of airflow propagation across the Ross Ice Shelf. This work highlighted the role of synoptic forcing to support the propagation of the airflow across the ice shelf and indicated that the warm infrared satellite image signature associated with these events does not necessarily reflect enhanced turbulent mixing of the strong inversion associated with the strong winds as had been previously thought. For this case the warm infrared satellite signature was due to the presence of low clouds. Nigro et al. (2012) used AWS observations, satellite imagery, and AMPS output to diagnose the dynamics of a high wind event (Fig. 14) over the southern Ross Ice Shelf. Their work identified a barrier wind corner jet occurring where the topography of the Transantarctic Mountains protrudes onto the Ross Ice Shelf.

Observations from the Antarctic AWS network have also been utilized for glaciological studies to better understand the mass balance of the Antarctic ice sheet. Stearns and Weidner (1993) used AWS observations of wind speed, humidity, and temperature at two heights to estimate sensible and latent heat fluxes over the Ross Ice Shelf. Estimates of net annual sublimation and deposition based on the AWS-derived turbulent fluxes amounted to 20%–80% of the annual accumulation. Knuth et al. (2010) examined data from ADG on several AWS units on the Ross Ice Shelf to identify periods of changing snow depth at the AWS sites. By combining the ADG observations with other meteorological observations from the AWS, they partitioned the snow depth changes into those associated with precipitation and blowing snow.

Another motivation for the development of the Antarctic AWS network was to provide observational

FIG. 14. Sabrina AWS wind speed observations (solid line) and AMPS forecast 10-m wind speed (dashed line) for a portion of Sep 2009 (from Nigro et al. 2011).

data that could be employed to improve Antarctic weather forecasting. Turner et al. (1996) described results from the Antarctic First Regional Observing Study of the Troposphere (FROST) project. One goal of this project was to determine the strengths and weaknesses of operational analyses and forecasts over the Antarctic. They found that the inclusion of AWS data from the Antarctic Plateau improved the quality of the 500-hPa operational analyses. Holmes et al. (2000) analyzed observations from AWS sites over the Ross Ice Shelf to determine precursors to high wind events at the Pegasus ice runway, the main intercontinental runway for the U.S. Antarctic Program. They found that increasing temperature difference between the Pegasus North and Minna Bluff AWS sites preceded high wind events at the Pegasus runway and could help forecasters improve short-term (3–6 h) forecasts at the runway. Observations from the AWS network are utilized in both National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (J. Comeaux 2010, personal communication; P. Poli 2010, personal communication). They are also employed in AMPS and NCEP operational numerical modeling (J. Powers 2008, personal communication; D. Keyser, NCEP, 2008, personal communication).

FIG. 15. The number of all Wisconsin AWS units installed in the Antarctic over the past 30 years. Note this includes AWS via all communication methods (e.g., Argos, 900-Mhz modem, stand alone/record only) as well as all online and offline (installed but not operating) sites.

FIG. 16. Alexander Tall Tower! AWS is the first 30-m “tall tower” AWS with eight measurement levels.

AWS observations have been critical in evaluating NWP models used in the Antarctic. Guo et al. (2003) used AWS observations from across the continent to evaluate simulations performed with the Polar fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5; Bromwich et al. 2001; Cassano et al. 2001). Polar MM5 was the NWP model used in the initial version of AMPS (Powers et al. 2003). Monaghan et al. (2003) used AWS observations from the South Pole to evaluate AMPS and two global NWP model forecasts for the unprecedented midwinter flight to the

South Pole to rescue Dr. Ronald Shemenski. Nigro et al. (2011) used AWS observations from across the Ross Ice Shelf to evaluate the performance of AMPS under varied synoptic conditions. They found that the quality of AMPS forecasts varied as the synoptic conditions changed. Results from this work provided additional guidance to Antarctic weather forecasters regarding the reliability of AMPS forecasts for different weather regimes.

SUMMARY, FUTURE PLANS, AND CONCLUDING REMARKS.

The use of automatic weather stations in Antarctica for meteorological and other applications has been a success, with 68 AWS units installed around the Antarctic (Fig. 15). The AWS network has been used for a wide range of science activities as well as for weather forecasting. It is clear that automated observations will be a part of the future of Antarctic meteorology, for both research and operations. Future applications will be diverse, supporting traditional activities (climatological analysis, etc.) as well as new projects (surface chemistry, etc.). Yet, there are challenges to be met, such as funding for the network, changing electronics, errors and limits in observations, and power limitations to name a few. The use of COTS equipment for the core of the AWS leaves the network tied to the commercial product availability cycle.

In the near future, the recent availability of web cameras or all-sky cameras that are affordable and

work with lower power requirements are likely to be the next standard component on AWS units. Critical to this sensor's success will be the increased communications bandwidth to relay the imagery. The greater bandwidth available via the Iridium satellite system at a reasonable cost may allow this system to become a preferred communications platform where AWS units are not able to transmit data to a main station or hub via radio modems. The ever increasing demand for observations to be available if not in real time then near-real time while minimizing deployments to recover recorded observations will make any improved communications system an attractive alternative. Although the AWS's satellite transmitting system has changed little in recent years, stations will likely employ more than one means for collecting observations, by both transmitting observations and recording them on board the stations, as some newer systems do now.

Special AWS units with targeted science objectives will also be a future focus of the Antarctic AWS network. The Alexander Tall Tower AWS with multiple levels of instrumentation for computing fluxes is one current example (see Fig. 16). Stations historically in the network included those that examined subsurface snow temperatures or the details of the wind field in particular regions such as Terra Nova Bay, Adélie Land, or the Siple Coast. Current efforts with sensors are focused on including more radiation instrumentation, on both net broadband radiation and the individual upward and downward radiative fluxes. The increasing strain of additional sensors will push commercially available logging electronic cores to their limits. The demand for additional sensors requires funding to quality control and to maintain the data, along with expanding repositories and data distribution.

With limited resources, the future of the network will rely increasingly on collaborations and interactions. AWSs are not unique to the Antarctic, as they are utilized worldwide for a variety of applications. Taking lessons learned in both the polar and AWS communities at large and applying them, as appropriate, to the Antarctic will benefit the network and improve observations and data applications. Antarctic meteorological community meetings such as the annual Antarctic Meteorological Observation, Modeling and Forecasting Workshop (AMOMFW) and Polar Technology Conference (PTC), provide a vehicle for discussing, initiating, and coordinating collaborations within the USAP and with international partners. Although NSF almost exclusively funds the Wisconsin AWS network with some

logistical support from other national Antarctic programs, collaborations with other autonomous observing systems should be employed because it reduces logistics costs and has mutual benefits for multiple communities (APOS 2011). As can be seen in Fig. 12, complete surface observations of the Antarctic require more than a single network. Multiple networks, supported by multiple projects across multiple national Antarctic programs, provide the rich albeit sparse network of observations relied upon for scientific research and operational forecasting. The future of the network depends upon the commitment and demands of the Antarctic community.

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