https://doi.org/10.5194/essd-2022-241
Preprint. Discussion started: 11 August 2022

The AntAWS dataset: a compilation of Antarctic automatic weather station observations

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Abstract. A new dataset of meteorological records from Antarctic automatic weather stations (here called AntAWS dataset) at 3-hourly, daily and monthly resolutions is constructed with quality control. This dataset compiles the measurements of air temperature, air pressure, relative humidity, and wind speed and direction from 216 AWSs available during 1980-2021. Their spatial distribution remains heterogeneous, with a majority of instrumented sites located on the coastal areas, and less at the inland East Antarctic Plateau. Among the 216 AWSs, 55 of them have the records spanning more than 20 years, and 25 of them spanning more than 30 years. Among the five meteorological parameters, the air temperature measurement data have the best continuity and the highest data integrity. The comprehensive compilation of AWS observations has the main aim to make them easy and time-saving to be used for local, regional and continental studies, which can be accessed at https://doi.org/10.48567/key7-ch19 (Wang et al., 2022). This dataset will be valuable for better characterizing surface climatology throughout the continent of Antarctica, improving our understanding of Antarctic surface snow-atmosphere interactions, and estimating regional climate models or meteorological reanalysis products.

1 Introduction

In the context of global warming, Antarctica plays an increasing role in the global sea level rise, atmospheric circulation, heat balance and climate evolution, and thus becomes one of the most important research focuses in the world (e.g., Wild et al., 2003; Chen et al., 2013). In recent decades, much attention has been paid to changes in the meteorological elements such as air temperature, snow accumulation, and wind speed over the Antarctic continent (IPCC, 2021), because they have profound impact upon the surface energy balance, ice sheet mass changes, as well as the ecosystem of its surroundings (e.g.,

https://doi.org/10.5194/essd-2022-241
Preprint. Discussion started: 11 August 2022

Giovinetto et al., 1990; Gregory et al., 2006; Herbei et al., 2016; Convey et al., 2018). To quantify these variations and trends, accurate and continuous weather measurements are a vital prerequisite.

Extensive efforts have been made to obtain continuous meteorological observations in Antarctica since the International Geophysical Year (IGY) in 1957/1958. For example, a total of approximately 50 staffed stations were established at the end of the IGY in 2007, of which 17 have continuous meteorological records to date (Summerhayes et al., 2008). Nevertheless, the majority of the stations are concentrated along the coast, and only seven stations are located in the interior of the Antarctic continent (Allison et al., 1993), which are not sufficient to present the Antarctic inland meteorological conditions. At the same time, harsh weather conditions and unique geographical topography of Antarctica make it extremely difficult to install and maintain staffed weather stations. Automatic weather stations (AWSs) allow monitoring in remote areas despite severe weather conditions, and help to fill the gaps of staffed weather observations (Stearns et al., 1988; Allison et al., 1993; Stearns et al., 1993; Reijmer et al., 2002; Renfrew et al., 2002). For the sake of intensively exploring the situations of the weather and climate throughout the Antarctic continent, a completely functional AWS network is still highly required (Lazzara et al., 2013).

In the late 1970s, advances in satellite communications and electronics techniques made it possible to receive AWS transmission from outer space, and thus real-time or near real-time meteorological data could be obtained in distant places. Benefited by this, numerous countries began to independently develop AWSs in Antarctica to support meteorolocial observations, glaciological research, and monitoring projects. In 1979, the United States Antarctic Program (USAP), supported the University of Wisconsin-Madison to launch the deployment of AWSs in Antarctica beyond an initial landmark research effort by Stanford University, mainly located in the Ross Ice Shelf and the West Antarctic Ice Sheet (Stearns et al., 1993; Lazzara et al., 2012). Mostly in Lambert Glacier drain of East Antarctica, an AWS network was established by The National Antarctic Research Expedition (ANARE) of Australia (Allison et al., 1993). Over the Antarctic Peninsula and Dronning Maud Land, the British Antarctic Survey and the Institute for Marine and Atmospheric Research, Utrecht University (IMAU) installed their respective AWS network. There are other AWS networks in the Antarctic that are not included in this project (e.g. Japan, France, Germany, South Korea, etc.). Despite the different design of AWSs from different nations, it is common that all stations measure air temperature, pressure, relative humidity, and wind speed and direction.

Given the funding constraints of different national Antarctic programs, AWS provides the most economical way to collect critical weather data to support ongoing applications, field activities and the planning of maintenance visits. Early scientific studies based on AWSs focused on the local meteorological processes and climatology of some basic parameters, such as temperature, pressure and wind (Stearns et al.,1993; Allison et al.,1993; Aristidi et al., 2005; Seefeldt et al., 2007). Over the AIS (Antarctic Ice Sheet), there are still missing data values at each AWS, which are a constraint for the climatological studies. Spatial and temporal interpolations are often used to fill the data gaps, and as a result, some continuous time series of meteorological elements have been created (e.g., Shuman and Stearns, 2001; Bromwich et al., 2013, 2014; Reusch and Alley, 2004). In addition, the AWS observations have also been used to evaluate and validate reanalysis products, regional climate models and remote sensing retrievals (e.g., Gallée et al., 2010; Tastula et al., 2012; Wang et al., 2013; Huai et al., 2019). Antarctic AWSs observations are also used in glaciological research, such as estimation of snow

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accumulations (e.g., Wang et al., 2021), calculation of the surface energy balance (e.g., van Wessem et al., 2014), and understanding the AIS mass changes (e.g., Knuth et al., 2010).

To better characterize the regional or even continental weather or climate status over Antarctica, a lot of attempts have been made to compile all available past and present AWS observations into the Antarctic Climate Data Database. Jacka et al. (1984) carried out the pioneering work to compile all annually and monthly averaged temperature observations of Antarctic and South Pacific island stations. Jones et al. (1987) assembled an integrated annual and monthly mean sea level pressure and temperature dataset from 29 weather stations located at 60°S-90°S. Stearns et al. (1993) provided a detailed description of the monthly mean climate data including monthly mean and extreme values of temperature, pressure, wind speed and direction collected and processed by the Antarctic AWSs at the University of Wisconsin. The dataset is being continuously updated. Turner et al. (2004) described the Reference Antarctic Data for Environmental Research (READER) by the Scientific Committee on Antarctic Research (SCAR). The dataset includes the monthly and annual mean near-surface air temperature, pressure and wind speed data from 43 staffed stations and 61 AWSs. Rodrigo et al. (2013) compiled Antarctic surface wind observations from 115 AWSs to assess the performance of regional climate models, and ERA-40 and ERA-Interim reanalysis products. Despite these existing AWS observation compilations, they generally suffer from part or all of the following limitations: the duration of datasets, single meteorological parameter, low temporal resolution, limited spatial coverage, no rigorous quality control and in some cases limited availability for the public.

In this study, our main goal is to use all available records from AWSs to construct a comprehensive quality-controlled database of Antarctic meteorological parameters including air temperature, pressure, relative humidity, and wind speed and direction. The database is 3-hourly, daily, and monthly resolved. We describe the methods used to generate this dataset, including record inclusion criteria and data quality control. In addition, the main temporal and spatial features of the database are summarized.

2 Automatic weather station system

AWSs are ground-based meteorological data collection devices, which can run without any interference all year round. All Antarctic AWSs are similar in design. They are equipped with a set of standard independent sensors, following the standards of the World Meteorological Organization (WMO, 2018). The AWS system used by the Antarctic Meteorological Research Center (AMRC) is mainly CR1000 series, which is a commercial off the shelf system wired and programmed much like the original AWS 2B series. The CR1000 series have the ability of keeping track of additional weather observations on AWSs that the AWS 2B system does not such as snow accumulation and incoming sunshine. AWSs created by the British Antarctic Survey (BAS) also use the CR1000 series for measurements. The Institute for Marine and Atmospheric Research, Utrecht University (IMAU) Antarctic AWS Project also use CR1000 systems to a large extent and a homemade system. Most of the AWSs of the Italian National Antarctic Research Programme (PNRA) are constituted by acquisition and control units provided by Vaisala series. The glaciology program of the Australian Antarctic Division (AAD) has designed and built three different types of AWSs during the past 20 years, with the latest version being series 098 AWSs. AWSs of the Chinese National Antarctic Research Expedition (CHINARE) consist of standard components provided by Campbell and Vaisala series, except XFY3-1 sensor (domestic propeller anemometer). Most of aforementioned sensors are mounted on a tripod of the stations. The AWS tripod body is made up of a mast, usually with instrument arms fitted with different sensors. The AWS controller, satellite transmitter, pressure sensor, power regulating circuit and battery are general installed in a box (or a series of boxes) at the bottom of the mast. In summer, the battery is charged by a small solar panel installed vertically near the top of the mast. However, the sensors of the AMRC AWS are mounted on the Rohn tower, and similar towers have been used by others. Table 1 presents the different types of sensors used on the AWSs and the corresponding detailed techniques. Although the measuring instruments of AWSs from different observation networks are different, the measuring range, accuracy and resolution are identical or nearly similar. Fig.1 shows the typical AWSs in four Antarctic research projects, but other sites may have parts of different sensors depending on the local environment.

AWS usually stores meteorological observation data on data logger convenient for maintenance (e.g., DT50, CR1000, Campbell Scientific logger), and transmits them through the Advanced Research and Global Observation Satellite network (ARGOS) , carried by the NOAA and Metop series of near polar orbit satellites. Fig.2 shows the data acquisition diagram of AWS, taking AMRC as an example. One of the ways AMRC receives the ARGOS data (the archive data) is through FTP services, including repeated and incorrect data transmission. If necessary, these data are regularly processed into meteorological values, and then repeated and incorrect data are compiled by internal software. AMRC also has a set of AWS using the Iridium communications system that is close to this.

Each AWS measures air temperature, pressure, relative humidity and other meteorological elements at a nominal height of approximately 3 meters, except for Zhongshan Station, which measures wind speed and wind direction at a height of 10 meters. Due to the accumulation or melting of snow, the measurement height of each meteorological element varies over time, and its uncertainty is evaluated to be about ±1 cm or 0.4% of the distance to the ground (Eisen et al., 2008). Parts of AWS devices also measure air temperature, wind speed and other variables at different heights to provide near ground vertical gradient data, which is convenient to check the accuracy of data and the redundancy of certain sensors. Some AWSs have added the sensors exploring snow temperatures at different depths, solar radiation and snow height, as well as a series of internal management parameters, such as voltage and internal temperature (see Fig.1).

Cost-effective AWSs provide timely research data from remote areas of Antarctica throughout the year. The minimal maintenance is still needed, and generally one visit is performed per summer to ensure that electric power generation and battery capacity are sufficient for polar night operation. However, several AWSs are not revisited after initial deployment. For example, since its first deployment in October 1984, AWS GC41 has been operating continuously in the interior of Antarctica with no maintenance access. The accuracy of the data from these sites can only be estimated by the internal consistency of the diverse sensors.

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Table 1. The sensor types used on the automatic weather stations and the technical specifications.

Institution	Sensor	Type	Specifications		
			Range	Resolution	Accuracy
AMRC	Air temperature	Weed PRT Two-wire bridge	to -100°C minimum	0.125°C	±0.5°C
		RM Young 43347 RTD 1000-ohm PRT	to -100°C minimum	0.01°C	±0.3°C
		Apogee ST-110 Thermistor	to -100°C minimum	0.01°C	0.1°C above 0°C 0.15°C below 0°C
	Relative humidity	Vaisala HMP14UT	0 to 100%	0.04%	±4%
		Vaisala HMP31UT Vaisala HMP35A/D Vaisala HMP45A/D	0 to 100%	0.04%	±2% above -20°C
		Vaisala HMP155	0 to 100%	0.04%	±2% above -40°C ±5% above -40° to -60°C
	Air pressure	Paroscientific Model 215 A	0 to 1100 hPa	0.04 hPa	±0.1 hPa
		CSI 105/PTB101	0 to 1100 hPa	0.1 hPa	±3 hPa
		CSI 106/PTB110	500 to 1100 hPa	0.1 hPa	±1.5hPa
	Wind speed	Bendix Model 120 Aerovane Belfort Model 122/123	0 to 60 m s^{-1}	0.25 m s^{-1}	±0.5 m s-1
		RM Young 05103/106	0 to 60 m s^{-1}	0.2 m s^{-1}	±0.5 m s^{-1}
		Taylor Model 201 High Wind System	0 to 60 m s^{-1}	0.33 m s^{-1}	±2 m s^{-1}
	Wind direction	Bendix Model 120 Aerovane Belfort Model 122/123 RM Young 05103/106/ Taylor Model 201 High Wind System	0 to 360°	1.5°	±3°
PNRA	Air temperature	Vaisala HMP45C/D	-40 to +60°C	-	±0.2°C
		Vaisala HMP155	to -80°C minimum	-	(0.2260-0028*Ta) °C
	Relative humidity	Vaisala HMP45D	0 to 100%	0.04%	±2% above -20°C

		Vaisala HMP155	0 to 100%	0.04%	±2% above -40°C ±5% above -40° to -60°C
	Air pressure	CS106 Barometer	500 to 1100 hPa	0.1 hPa	±1.5 hPa (-40 to +60°C)
		BARO1	500 to 1100 hPa	0.01 hPa	±0.15 hPa (-40 to +60°C)
		PTB200	600 to 1100 hPa	0.01 hPa	±0.15 hPa (-40 to +60°C)
	Wind speed	Vaisala WAA151	0.4 to 75 m s^{-1}	-	±0.5 m s^{-1}
		RM Young 05103/106	0 to 60 m s-1	0.2 m s-1	±0.5 m s-1
	Wind direction	Vaisala WAV151	0 to 360°	2.8°	±3°
		RM Young 05103	0 to 360°	1.5°	±3°
IMAU	Air temperature	Vaisala HMP35AC	-80 to +56°C	-	±0.3°C
	Relative humidity	Vaisala HMP35AC	0 to 100%	-	±2% (RH<90%) ±3% (RH>90%)
	Air pressure	Vaisala PTB101B	600 to 1060 hPa	-	±4 hPa
	Wind speed	RM Young 05103	0 to 60 m s^{-1}	0.2 m s-1	±0.5 m s-1
	Wind direction	RM Young 05103	0 to 360°	1.5°	±3°
AAD	Air temperature	FS23D thermistor in ratiometric circuit	-99 to +13°C	0.02°C	±0.05°C
	Relative humidity	Vaisala HMP35D	0 to 100%	2%	±2% (RH<90%) ±3% (RH>90%)
	Air pressure	Paroscientific Digiquartz 6015A	530 to 791 hPa	0.1 hPa	±0.2 hPa
	Wind speed	3-cup anemometer with R M Young 12170C cup set, and AAD built body and mechanism	0 to 51 m s^{-1}	0.1 m s^{-1}	±0.5 m s^{-1}
	Wind direction	Aanderaa 3590B wind vane Aanderaa 2750	0 to 360°	6°	±6°
BAS	Air temperature	CSI RTD 100-ohm PRT	to -100°C minimum	0.01°C	±0.5°C
		Weed PRT Two-wire bridge	to -100°C minimum	0.125°C	±0.5°C
		Vaisala HMP35D/45D	-40 to +60°C	-	±0.2°C
	Relative humidity	Vaisala HMP35D	0 to 100%	2%	±2% (RH<90%) ±3% (RH>90%)

		Vaisala HMP45A/D	0 to 100%	0.04%	±2% above -20°C
	Air pressure	Paroscientific Model 215 A	0 to 1100 hPa	0.04 hPa	±0.1 hPa
	Wind speed	Impeller-vane anemometer	-	-	-
		Belfort Model 122/123	0 to 60 m s^{-1}	0.25 m s^{-1}	±0.5 m s^{-1}
		RM Young 05103/106	0 to 60 m s^{-1}	0.2 m s^{-1}	±0.5 m s^{-1}
	Wind direction	Impeller-vane anemometer	-	-	-
		Belfort Model 122/123 RM Young 05103/106	0 to 360°	1.5°	±3°
CHINARE	Air temperature	HMP155	to -80°C minimum	-	(0.2260-0028*Ta) °C
		Campbell 109	-	-	(0.2260-0028*Ta) °C
		FS23D thermistors	-99 to +13°C	0.02°C	±0.05°C
		Weed PRT Two-wire bridge	to -100°C minimum	0.125°C	±0.5°C
	Relative humidity	HMP155 resistance probe	0 to 100%	0.04%	±2% above -40°C ±5% above -40° to -60°C
		HMP35A/D	0 to 100%	0.04%	±2% above -20°C
	Air pressure	CS106 Barometer	500 to 1100 hPa	0.1 hPa	±1.5 hPa (-40 to +60°C)
		PTB110	0 to 1100 hPa	0.1 hPa	±1.5hPa
		PTB210	-	-	±0.5hPa
		6015A	530 to 791 hPa	0.1 hPa	±0.2 hPa
		Paroscientific Model 215 A	0 to 1100 hPa	0.04 hPa	±0.1 hPa
	Wind speed	XFY3-1	0.3 to 50 m s^{-1}	-	±1m s^{-1}
		12170C	0 to 51 m s^{-1}	0.1 m s^{-1}	±0.5 m s^{-1}
		RMYoung	0 to 60 m s^{-1}	0.2 m s^{-1}	±0.5 m s^{-1}
	Wind direction	XFY3-1	0 to 360°	-	±5°
		10K Ohmpot	0 to 355°	1.5°	±3°
		3590B	0 to 360°	6°	±6°

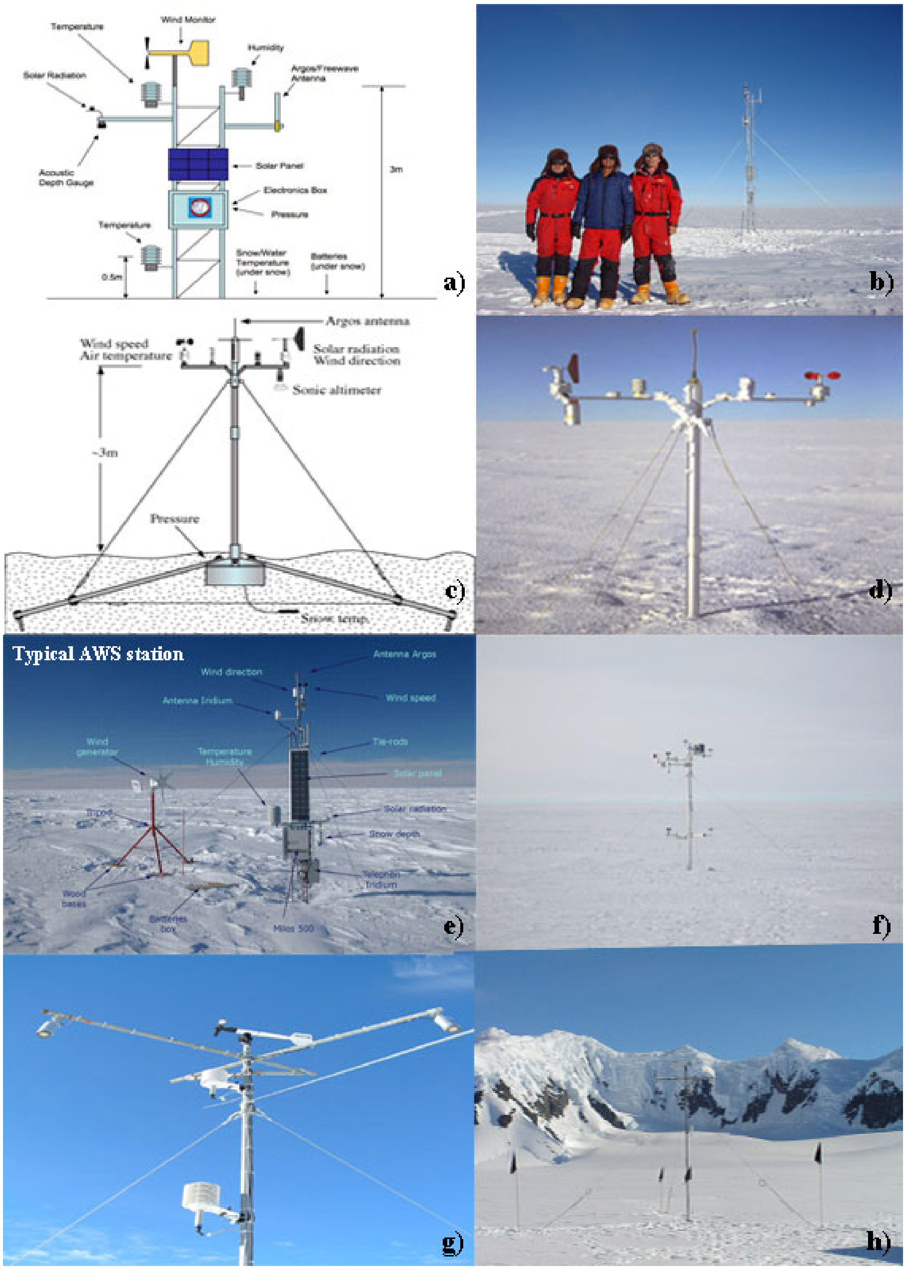
Temperature
Wind Monitor
Humidity
Solar Radiation
Argos/Freewave Antenna
Acoustic Depth Gauge
Solar Panel
Electronics Box
Pressure
3m
Temperature
0.5m
Snow/Water Temperature (under snow)
Batteries (under snow)
a)
b)
Argos antenna
Wind speed
Air temperature
Solar radiation
Wind direction
Sonic altimeter
~3m
Pressure
Snow temp.
c)
d)
Typical AWS station
Antenna Argos
Wind direction
Antenna Iridium
Wind speed
Wind generator
Temperature Humidity
Tie-rods
Solar panel
Tripod
Solar radiation
Snow depth
Telephon Iridium
Wood bases
Batteries box
Milos 500
e)
f)
g)
h)

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Fig.1. Typical AWSs of the six research institutions, but the sensors at other sites vary slightly depending on the local environment. a) AMRC-CR1000 system, b) AMRC and CHINARE-Panda_South, c) IMAU-type I station, d) IMAU-AWS10, e) PNRA-typical AWS station, f) AAD and CHINARE-Eagle, g) BAS-the sensors used on Latady, h) BAS-Latady.
a) http://amrc.ssec.wisc.edu/news/2010-May-01.html
b) and f) personal communication with Minghu Ding.
c https://www.projects.science.uu.nl/iceclimate/aws/technical.php
d) https://www.projects.science.uu.nl/iceclimate/aws/technical.php
e) https://www.climantartide.it/attivita/aws/index.php?lang=en
g) and h) https://ramadda.data.bas.ac.uk/repository/entry/show?entryid=synth%3A44d1a477-0852-4620-a1f4-63f559b44e94%3AL0RvY3VtZW50cy9waG90b3NfYXdz

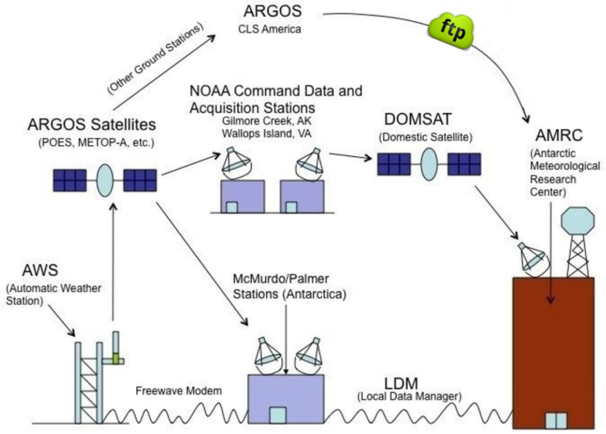

Fig.2. Data acquisition diagram of AWS, using AMRC as an example.
http://amrc.ssec.wisc.edu/aws/images/datastream_v2.jpg

3 Data processing

3.1 Data collections and sources

The AWS meteorological observations were obtained from six Antarctic AWS project databases, including the Chinese National Antarctic Research Expedition (CHINARE), the British Antarctic Survey (BAS) (https://data.bas.ac.uk/datasets.php), the Italian National Programme of Antarctic Research (PNRA) (http://www.climantartide.it), the Institute for Marine and Atmospheric Research, Utrecht University (IMAU) Antarctic AWS Project (https://www.projects.science.uu.nl/iceclimate/aws/antarctica.php), the Australian Antarctic Division Glaciology Program (AAD) (http://aws.acecrc.org.au/), and the Antarctic Meteorological Research Center (AMRC) (http://amrc.ssec.wisc.edu/) at the University of Wisconsin (Lazzara et al., 2012). The

AMRC was also assisted by several Antarctic research programs, such as the Japanese Antarctic Research Expedition (JARE), the French Antarctic Program (Institut Polaire Francais-Paul Emile Victor, IPEV), the AAD, the BAS and the CHINARE. The JARE was responsible for installing and maintaining the JASE2007, Dome Fuji, Mizuho and the Relay Station on the East Antarctic Plateau. The IPEV installed and took charge of the AWSs from the Adelie Coast to Dome C II, including the Port Martin, D-10, D-17, D-47, D-85, Dome C and Dome C II. The cape Denison on the Adelie Coast was cooperated by AAD and AMRC. The BAS was in charge of maintaining the AWSs on the AP and the East Antarctic Plateau, including the Butler Island, Larsen Ice Shelf, Limbert, Sky-Blu, Fossil Bluff, Dismal Island and the Baldrick. The Panda South station, located on the East Antarctic Plateau, was a cooperation between CHINARE and AMRC, which was installed, maintained and operated by CHINARE. In addition, Eagle and Dome A station were collaborated by CHINARE and AAD.

First, we excluded AWS stations with data coverage of smaller than one year. Then, all available records from the remaining stations were collected. Finally, 216 AWS measurements were compiled, including at least one of the five meteorological variables: near surface air temperature, relative humidity, air pressure, wind speed and wind direction. Fig.3 shows the spatial distribution of the 216 AWSs, and the corresponding longitude and latitude coordinates, elevation and data sources of these AWSs are summarized in Table S1.

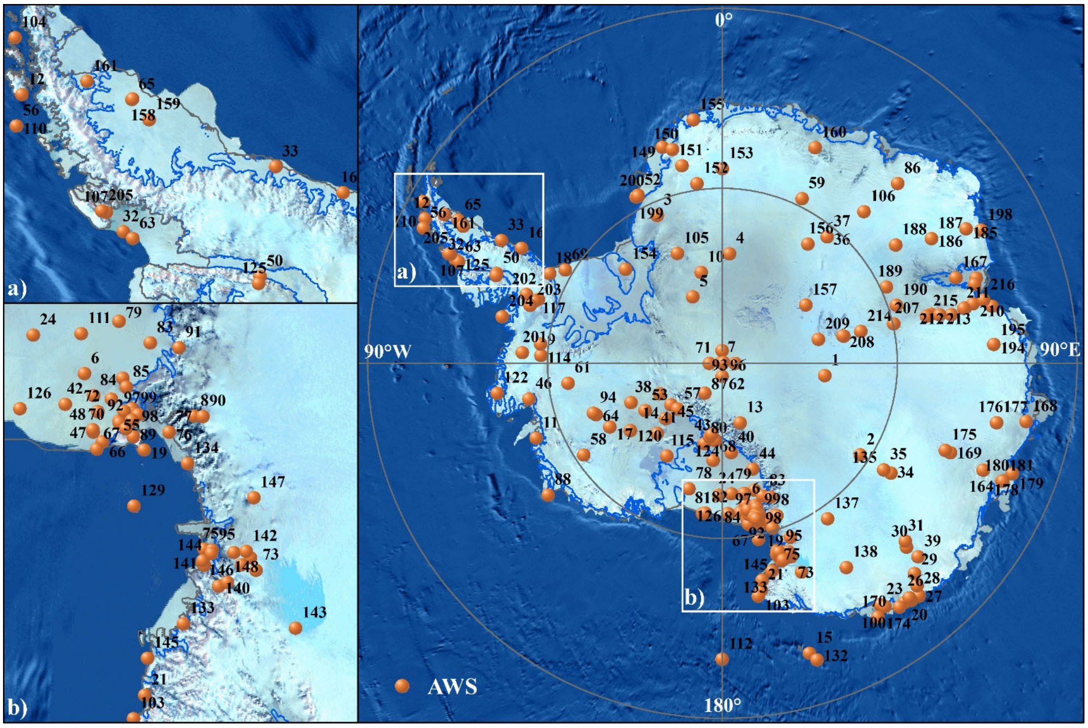

Fig.3. Mapping the sites of 216 Automatic Weather Stations (AWSs)

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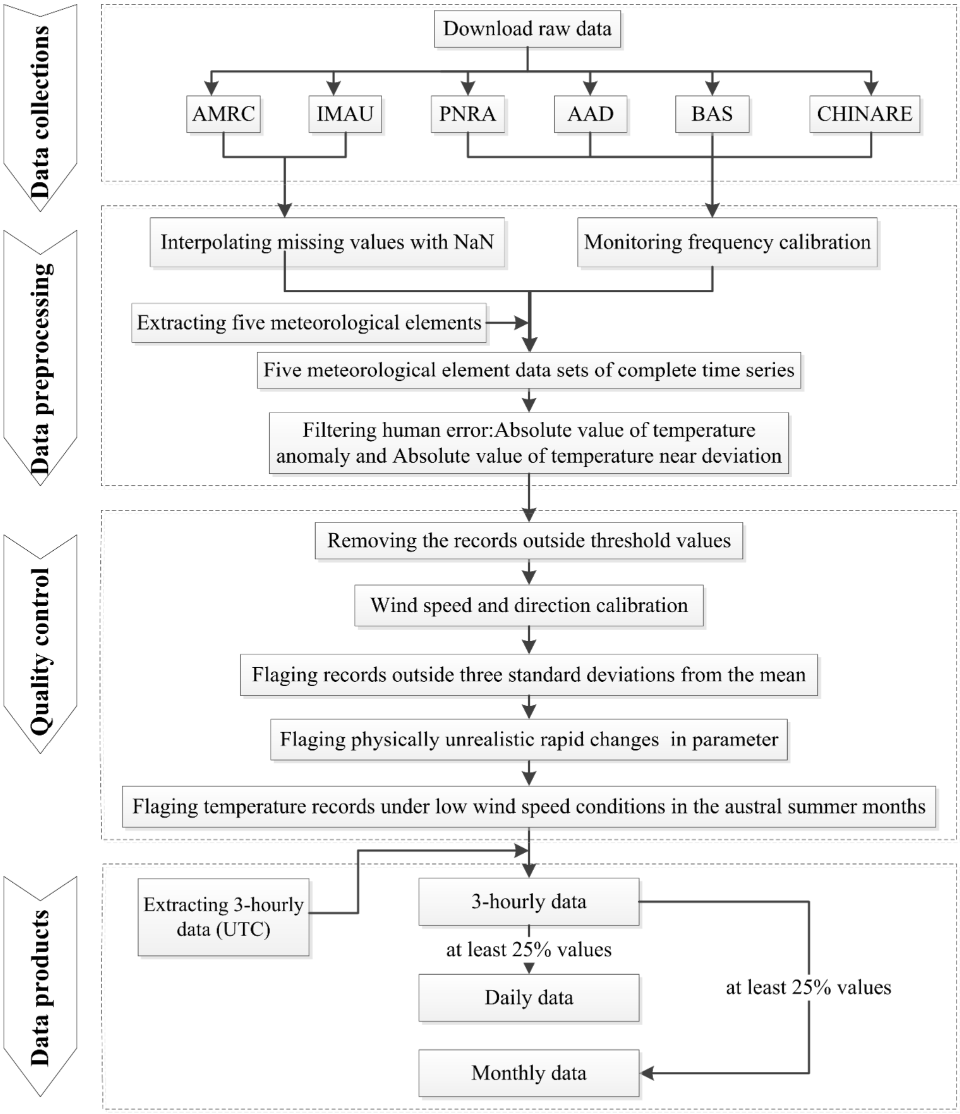

206
207 Fig.4. Description of AWSs data processing process.

3.2 Quality control

Quality check of observational data is aimed at detecting missing data and errors to provide the highest possible standard of accuracy. Our compilation is based on the hourly and 3-hourly synoptic measurements from AWSs, which were subjected to quality check by data providers, including a coarse error check using threshold values at the time of decoding, and manually filtering errors or gaps due to the presence of instrument failures such as sensor freezing and screen covered by snow/frost, the problems of transmission through datalogger, Global Telecommunications System (GTS) or ARGOS, and changes in units, and so on. Despite the quality checks, previous studies pointed out that cautions should be made on using these AWS data, at least wind speed data, which are the least reliable variable of the measurements (e.g., Stearns et al.,1993). To perform a more rigorous quality control, a set of interactive quality control programs using interactive data language (IDL) software was developed for the quality check of the AMRC data (Lazzara et al., 2012). In our compilation, we use the 3-hourly AMRC AWS data through preliminary quality control. Since our objective was to construct a dataset with high quality, restrictive quality control criteria were used to filter the compiled data from a variety of sources.

First, we removed the records from the dataset outside the measurement range of sensors installed over the AWSs (Table 2). Data with zero values for both wind speed and direction were also eliminated. Furthermore, if the wind speed and direction values remained unchanged for 6 consecutive hours which are likely caused by sensor freezing, the values were set to the null values (NA). Secondly, the mean and standard deviation were calculated for the 3-hourly data in each month. We also check physically unrealistic rapid synoptic variability in the parameters using the 6-h change threshold values of 10 hPa for surface pressure, 5ºC for air temperature, 40 kt for wind speed (Turner et al., 2004). Following Lazzara et al. (2012), the observation values exceeding three standard deviations from the mean were regarded as the possible errors, and thus were flagged. Thirdly, we flagged the air temperature records in the austral summer months (December-January-February) during the low-wind speed conditions (less than 2 m s^{-1}), which can result in the temperature overestimate during this period because of the lack of ventilation (Genthon et al., 2011; Lazzara et al., 2012; Jones et al., 2016).

Table 2. Threshold values used in the quality control process for each measured variable.

Variable	Units	Low threshold	High threshold
Temperature	℃	-100	15
Pressure	hPa	0	1100
Wind Speed	m/s	0	60
Wind Direction	°	0	360
Relative Humidity	%	0	100

3.3 Averaging procedure

For all meteorological parameters, daily and monthly mean values are calculated by the 3-hourly data (eight values a day, between 00:00 and 21:00 UTC). Unfortunately, a number of events that occur while AWS is unattended may result in data gaps. For daily value to be included, at least two 3-hourly observed values (25%) are available. As less than 25% of the 3-hourly observations do not well capture the weather

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conditions of the day, a good daily average cannot be obtained. Then, if at least 25% of the 3-hourly observations are available in a month, we calculate a monthly average. For monthly data, less than 25% of the 3-hourly observed value typically occurs when a station starts or stops during the month, which may lead to the deviation of the monthly average, especially in the period of rapid changes in meteorological elements such as air temperature. All missing values are set to NA.

4 Description of the AntAWS dataset

4.1 Air temperature

Air temperature is a sensitive indicator of the climate extremes experienced by the whole continent, which is measured at heights of approximately 3 m above the ground based on the resistive platinum probe. The probe is located at the tip of the sensor. The air temperature sensor is installed in the AWS' naturally ventilated radiation shields to protect the sensor from direct sunlight, and the measurement uncertainty is within ±0.5℃.

Fig.5 and Table S2, Table S3, Table S4 show the mean, maximum and minimum values of 3-hourly, daily, and monthly air temperature from each AWS. The overall statistical results show that affected by sea-land distribution and elevation, the air temperature in coastal areas is generally higher than that in inland areas, showing a gradual decrease from coastal to inland areas. Fig.5 and Table S2 show that the mean temperature of 3-hourly data ranges from -58.8℃ to -1.5℃. The extreme maximum temperatures of the Antarctic Peninsula, most of the West AIS, Ross Ice Shelf and Victoria Land are almost all over 0℃. The warmest AWSs are aws10 and Pegasus South with elevations of 890 m and 5 m respectively, and the maximum temperature can reach 15℃. The AWSs with extreme minimum temperatures below -70℃ are mainly distributed in the East Antarctic Plateau. The minimum temperature value is lower than -82℃, occurring in aws12, aws13, Dome C, Dome F and Concordia. Statistics of the daily air temperature indicate that the daily mean air temperature values range from -56.9℃ to -1.3℃ (Table S3). The maximum daily temperature occurs at aws10 station on the Berkner Island, reaching 14.8℃. The lowest daily temperature is -83.5℃ at aws13. According to the statistical results of monthly data in Table S4, the mean temperature of monthly data ranges from -59.1℃ to -1.4℃. The aws10 station still has the highest monthly averaged air temperature of 8.7℃. Concordia, located on the East Antarctic Plateau, has the lowest monthly temperature of -71.8℃.

4.2 Air pressure

Most of the AMRC AWS network uses Paroscientific digitquartz, which has excellent resolution of 0.04 hPa and accuracy (+/-0.1 hPa). Whereas most of AWSs at other institutions use Vaisala's PTB series and Campbell's CS series. Both series of barometers use Vaisala's BAROCAP silicon capacitive absolute pressure sensor, which have excellent accuracy, repeatability, and long-term stability over a wide range of operating temperatures. The barometer kept in the electronics enclosure measures the station pressure, and are not corrected to sea level. The accuracy of all air pressure measurements ranges from 0.15 hPa to 4 hPa, depending on the sensor used.

Fig.5 and Table S2 show the mean, maximum and minimum pressure of 216 AWSs at 3-hourly time resolution. The range of the mean air pressure values goes between 573.5 hPa and 991.7 hPa. AWSs with 3-hourly average pressure greater than 900 hpa are mainly located along the coast of the Ross Ice Shelf, Antarctic Peninsula, Dronning Maud Land, the Lambert Glacier Basin, Victoria Land, etc. The maximum 3-hourly air pressure (1035.8 hPa) appears at the station on the Larsen Ice Shelf of the Antarctic Peninsula. The minimum (545 hPa) is present at Kunlun station, with the elevation of 4093 m a.s.l.. Mainly affected by elevation, the mean, maximum and minimum air pressure spatially decreases from the coast to the interior. The major features of spatial distribution of daily and monthly air pressure are almost the same as those of 3-hourly data.

4.3 Relative humidity

The height of the humidity sensor is often the same as that of the air temperature probe. Correct measurements of air relative humidity are key to calculate sublimation. However, it is quite difficult to accurately measure, especially at Antarctica. The original network did not include such measurements, but humidity detectors (Vaisala HMP Series) have been deployed in the last decade. Humidity measurement is based on a capacitive thin film polymer sensor. The resolution of the series of humidity sensors is approximately 1%, and the annual drift in the field is approximately ±2 ~ 3%.

Many AWSs lack relative humidity measurements in consecutive years or entirely, which brings great challenges to humidity research of the whole Antarctic continent. However, relative humidity reports from the AntAWS network are found over the full range 0 to 100%. The relative humidity of the coastal AWSs is usually higher than that of the inland AWSs, and shows similar spatial patterns with air temperature.

4.4 Wind speeds and directions

Wind speeds and directions are monitored at a height of approximately 3 m above the ice sheet surface (Lazzara et al., 2012). It is notable that, at the Zhongshan station, the 10 m wind directions are measured. Due to the influence of katabatic wind, the wind directions at this station are relatively stable and resemble the 3m wind directions (Ma et al., 2014). Different sensors are used to measure wind speed and direction at the different AWSs. The most widely used model is R. M. Young Company 05103/106, in which wind speeds are measured using an impeller anemometer that is a helical, four-blade impeller. The rotation of the impeller generates a signal proportional to wind speeds, and wind directions are measured using a potentiometer. In addition, some AWSs adopt the heated Vaisala WA15 series, which is based on precise sensors mounted on cross arms. Its WAA151 anemometer has the characteristics of fast response and low threshold. Similarly, the optoelectronic vane-WAV151 has the advantages of counterbalance, sensitivity, accuracy and low threshold. It is more suitable for more demanding wind measurements. The measurement accuracy of wind speeds is approximately ±0.5 m s^{-1}, and wind direction is ±3°. The wind direction listed is clockwise from 0° to 360° (so 90° are east, 180° are south, and 270° are west). The stations established by CHINARE use a domestic propeller anemometer (XFY3-1 sensor), which can measure the wind speed and direction of horizontal airflow at very low critical wind speed, with the uncertainty of ±1 m s^{-1} and ±5°, respectively.

The results of Fig.5 and Table S2, 3 and 4 show that wind speed is consistent whether parsed in 3 hourly values or in daily, monthly values, and so is wind direction. The mean near-surface wind speeds of 216 AWSs vary from 0 to 23.4 m s^{-1}. The average wind speed is higher along the East AIS coast, where the average wind speed exceeds 20 m s^{-1} (e.g., Cape Denison and Zoraida stations). The average wind speed at the AGO-5, Dome C, Dome F, and Dome A stations on the Antarctic inland plateau is less than 3 m s^{-1}, mainly due to the gentler surface slopes of the inland plateau (Van den Broeke and Van Lipzig, 2003). The maximum wind speed (exceeding 60 m s^{-1}) is observed at Alessandra, Eneide, Lola, Rita, Silvia, Sofia, Sofiab, and Zoraida stations in North Victoria Land. Spatial patterns of wind speed are generally high along the coast and low at the inland ice sheet, which is mainly determined by the terrain and pressure gradient from coastal to inland. Southerly or easterly winds prevail over most of the AIS, influenced by circumpolar westerly winds, katabatic winds, large-scale pressure gradient forces and topography, which contributes to drive the movement of the AIS atmospheric boundary layer (Van den Broeke et al., 2002).

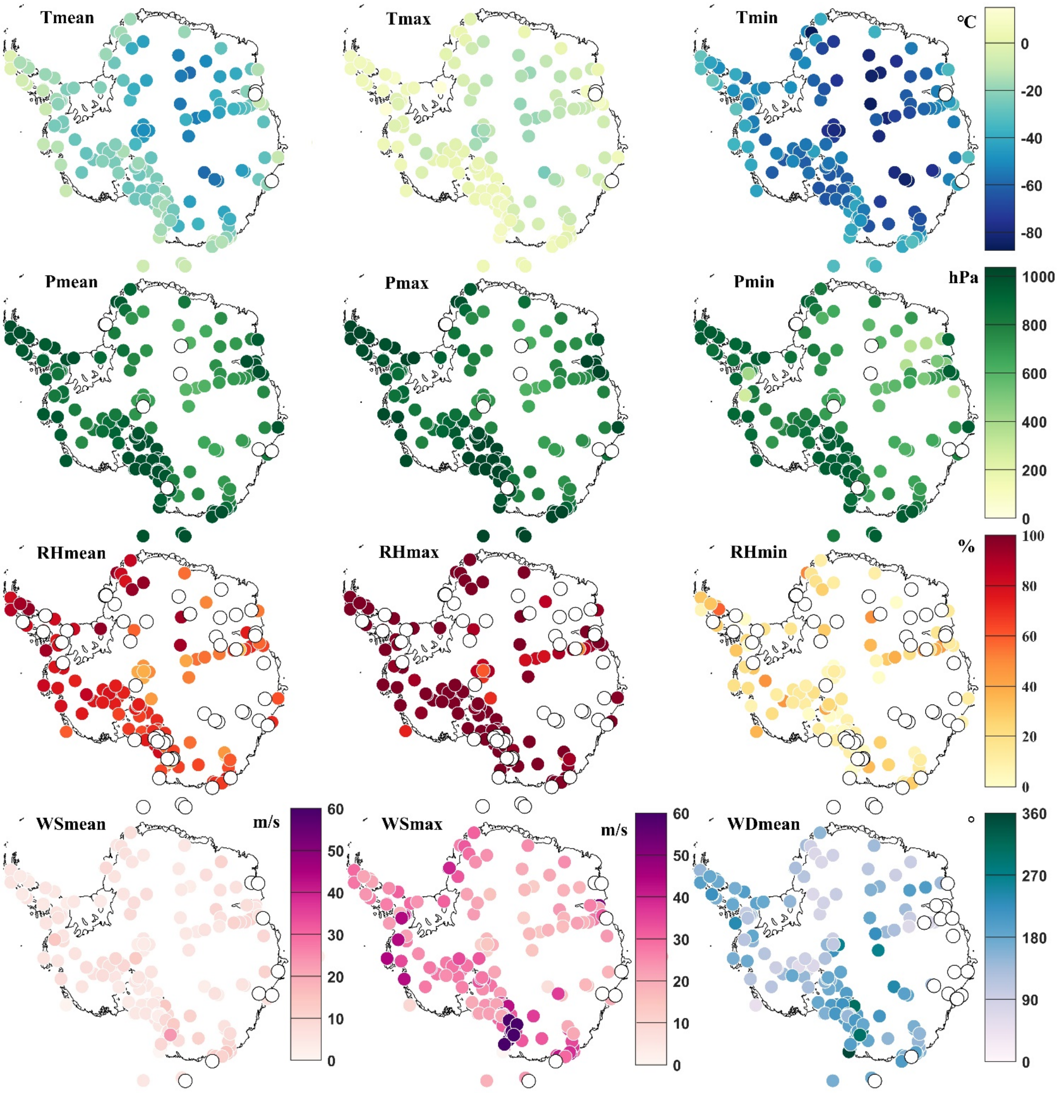

Fig.5. Spatial distribution of AWSs multiyear 3-hourly mean, maximum and minimum meteorological elements during 1980-2021.

5 Spatiotemporal characteristics of the AntAWS dataset

5.1 Spatial coverage of AWS records

Spatial distribution of AWSs is heterogeneous in the Antarctic Ice Sheet (AIS). On the whole, since 1980, the number and coverage of AWSs have been gradually increasing (see Fig.6, Fig.7, and Table S5). In 1980, there were only 9 AWSs, of which five were located in Ross Island Vicinity, two stations on the coast of Adélie Land, and two in inland Antarctica (Byrd and Dome C). The number and spatial coverage of AWSs that their data are available peak in 2011. In this year, a total of 101 AWSs were counted. Some high elevations of the Antarctic Plateau are documented, but approximately 90% of the AWSs were still mainly distributed in coastal areas. Among them, the densest regions covered by AWSs are the Ross Ice Shelf and Victoria Land, accounting for approximately 50% of AWSs in this year. The gradually improved AWS network has helped fill the wide gaps in climate observations across the whole Antarctic continent.

Despite the significant improvement of the spatial coverage of AWSs, the records of individual variables are still not regularly distributed, centering in specific areas of Antarctica (see Fig.5, Table S5). Air temperature and pressure are relatively easy to measure, have the highest data availability of any sensor, and have high integrity and wide spatial coverage. In contrast, the quality of air temperature data is the best, with only three stations missing air temperature measurement records. Measuring wind speed and direction is a huge challenge in Antarctica, due to covering such a wide range of speeds from calm/breeze to sustained hurricane intensity. The loss of wind speed and direction data mainly occur in the coastal areas of the Lambert Glacier Basin, Princess Elizabeth Land, Queen Mary Land and Wilkes Land. The humidity sensor may lose measurement accuracy at very cold temperatures, and their data loss is highest. In addition to the West AIS and near the South Pole, there are many AWSs that lack humidity measurements all year round in other parts of Antarctica.

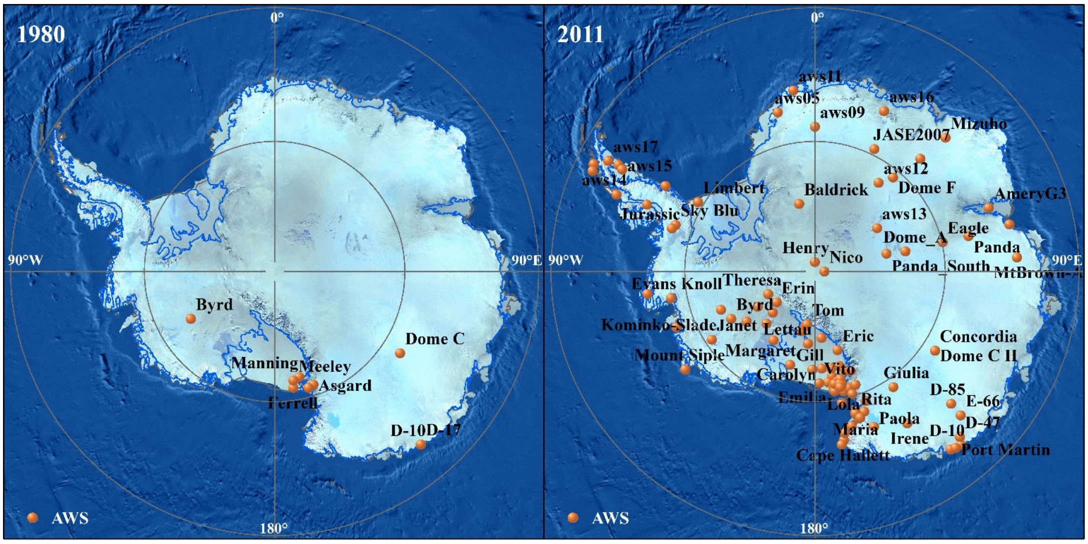

Fig.6. Spatial distribution of AWS in 1980 and 2011

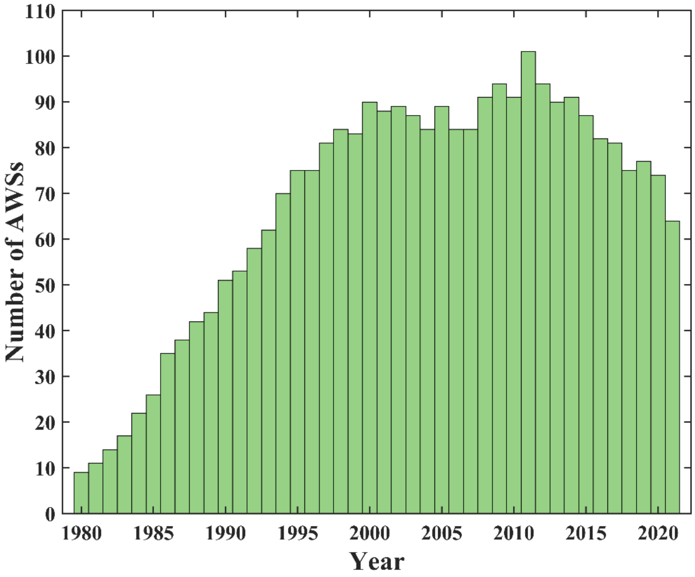

Fig.7. Number of AWSs counted each year.

https://doi.org/10.5194/essd-2022-241
Preprint. Discussion started: 11 August 2022

5.2 Temporal variability in the AWS records

The five meteorological elements of each AWS cover different time spans, from 1 year to 42 years. The time period covered is closely related to sensor technology and weather conditions. Statistical results in supplemental Table S5 show that the time span of 55 AWSs exceeds 20 years, of which 25 stations exceed 30 years, but approximately 28.7% of the AWSs still cover less than 5 years. For various reasons, most of the time series in the dataset have gaps for one or all of the meteorological elements (Fig.8).

Fig.8 and Fig.S1-S4 show the daily data availability of air temperature, air pressure, wind speed and relative humidity, respectively. Among the 216 AWSs, the air temperature measurement data have the best continuity and highest data integrity. Approximately 26% of the stations have more than 15 years of daily temperature measurement data. Furthermore, 195 stations have daily data integrity of more than 50%. In recent years, the improvement of air pressure sensor technology has greatly perfected the quality of air pressure measurement data. The integrity of daily pressure data of 185 meteorological stations exceeds 50%, and approximately 25% of stations have daily pressure data over a 15-year timespan. The wind sensor is obviously affected by temperature, and the resulting data has the poorest continuity of data. Only approximately 21% of the stations have the daily wind speed and direction data with a timespan of more than 15 years. There are 151 stations having daily wind speed and wind direction data integrity of more than 50%. For the 1980-2021 period, the lack of relative humidity data is the most serious, with 55 stations having no relative humidity data all year round, and only 119 stations with daily data integrity of more than 50%. Moreover, the data continuity is the lowest, with only 18% of stations measuring daily relative humidity covering more than 15 years.

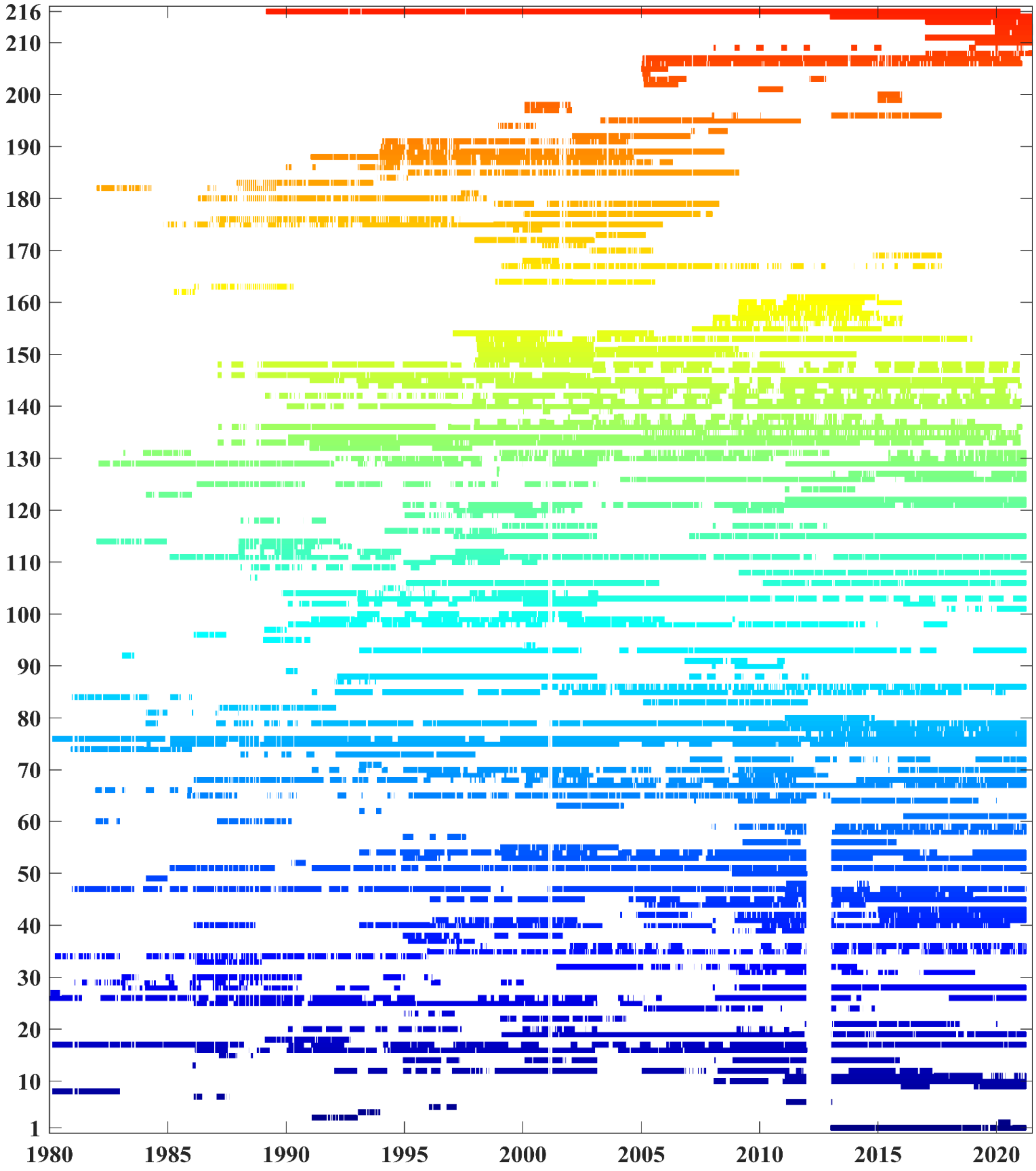
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Fig.8. Daily data availability of air temperature. The missing value has no colour, and 1-216 corresponds to NO. in Table S1.

6 Station documentation

The entire dataset consists of four subdatasets, including three quality-controlled subdatasets and one flagged subdataset of suspicious data in raw data, which are all provided in spreadsheet form. In quality-controlled daily and monthly subdatasets, all "wt" columns are the proportion of observations entered into the average value of the day or month. Number “1” indicates integrated continuous data without missing data. In the flagged subdataset, " flag_*" marks the suspicious data of each variable detected in Section 3.2 quality control. Number “4” indicates that the observed value exceeds the three standard deviations from the mean. A multiple of 100 represents the physically unrealistic 6-h rapid synoptic variability in the parameters. The air temperature records in the austral summer months (December-January-February) during the low-wind speed conditions (less than $2\ \mathrm{m\,s^{-1}}$) are flagged with number “10”. Time is in 3-hourly, daily and monthly formats, and the UTC time is used in the 3-hourly data files (UTC+8). At the same time, we also provide the data integrity of 3-hourly, daily and monthly data of each variable.

The raw data include four different data storage formats: ASCII format (.dat), NetCDF format (.nc), TXT format (.txt) and Excel format (.xlsx). Five meteorological elements are extracted and saved in comma separated values format (.csv format). CSV format is selected on account of simple file structure and storage mode, basic security, and extensive support in scientific applications, which is convenient for programming software (e.g., R) to process data in batches. The file names are composed using the station's name and data type. A file name such as AGO Site_3 h.csv can be read as station AGO Site, 3-hourly data, extension indicating CSV format data (.csv). The data are arranged in columns of Year, Month, Day, Three-hourly observation time (UTC), Temperature (℃), Pressure (hPa), Wind Speed (m/s), Wind Direction (°), Relative Humidity (%).

7 Data and code availability

The comprehensive AWS dataset is freely available as 3-hourly, daily, monthly data separated for each station at https://amrdcdata.ssec.wisc.edu/dataset/antaws-dataset (Wang et al., 2022). All codes for the AWS data quality control are developed in the *R* environment, which are available from the corresponding authors on a reasonable request.

8 Conclusions

We provide a comprehensive compilation of long-term measurements of the AIS AWSs. The dataset includes the locations, instruments used, and measurements of five parameters i.e., air temperature, air pressure, relative humidity, wind speed and wind direction, of 216 AWSs at 3-hourly, daily and monthly resolutions, covering most areas of the Antarctic continent from 1980 to 2021. Relative to earlier studies, our compilation presents better spatial coverage, although the spatial density is least over the East Antarctic Plateau.

We adopt a comprehensive quality control process to carefully check the data to maximize the reliability of the data. This results in the reduction in the temporal density of data in some AWSs. However, the statistical results of 216 AWSs from 1980 to 2021 show that the integrity of the 3-hourly air temperature and air pressure data from 159 stations exceeds 50%. Moreover, 113 stations have 3-hourly relative humidity data integrity of more than 50%, which is the variable of lowest data integrity. There are 74 stations with the integrity of the 3-hourly wind measurement data of less than 50%. This is easily understood as among the five variables, wind speed and direction observations have highest uncertainties caused by excessive speed, snow build-up and so on.

The dataset can provide more accurate and effective input and verification data for the validation of reanalyses, remote sensing products and regional climate models. At the same time, as done by Steig et al. (2009), by combining the dataset with reanalysis data or remote sensing products, gridded data products can be reconstructed, which can better display the temporal and spatial variation in the AIS meteorological elements at different scales, and provide basic data for the studies of Antarctic mass balance and climate changes. It is hoped that the dataset will facilitate glaciological, meteorological, hydrological, or other studies over Antarctica. In the future, with the continuous updating of AWSs data, we will further refine the dataset, adopt more rigorous quality control criteria, check the unrecognizable errors in the raw data, and even provide quality marks for the dataset.

Author contributions.

YW contributed the idea of this work and constructed the AntAWS dataset. XZ prepared the figures and tables based on the compiled data analysis. WN wrote the codes of data processing algorithm. MAL, MD, CHR, PCJPS, PG and ERT provided part of AWS observations for constructing the dataset. MAL and PG provided some necessary information of AWSs. ZZ and YS performed the primary data collections. SH supervised this work. XZ and YW wrote the original draft, which was improved by all other authors.

Competing interests.

All authors has declared that neither of them has any conflicts of interest.

Acknowledgements

Funding this work was the National Natural Science Foundation of China (41971081, 41830644 and 42122047), the National Key Research and Development Program of China (2020YFA0608202), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19070103), the Project for Outstanding Youth Innovation Team in the Universities of Shandong Province (2019KJH011) and the Basic Research Fund of the Chinese Academy of Meteorological Sciences (2021Y021 and 2021Z006).

This work is also supported by funding to the University of Wisconsin-Madison and Madison Area Technical College from the US National Science Foundation Office of Polar Programs (1924730, 1951720, and 1951603).

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