Automatic weather stations for basic and applied glaciological research

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Since the early 1980s, the Geological Survey of Denmark and Greenland (GEUS) glaciology group has developed automatic weather stations (AWSs) and operated them on the Greenland ice sheet and on local glaciers to support glaciological research and monitoring projects (e.g. Olesen & Braithwaite 1989; Ahlstrøm *et al.* 2008). GEUS has also operated AWSs in connection with consultancy services in relation to mining and hydropower pre-feasibility studies (Colgan *et al.* 2015). Over the years, the design of the AWS has evolved, partly due to technological advances and partly due to lessons learned in the field. At the same time, we have kept the initial goal in focus: long-term, year-round accurate recording of ice ablation, snow depth and the physical parameters that determine the energy budget of glacierised surfaces. GEUS has an extensive record operating AWSs in the harsh Arctic environment of the diverse ablation areas of the Greenland ice sheet, glaciers and ice caps (Fig. 1). The current GEUS-type AWS (Fig. 2) records meteorological, surface and sub-surface variables, including accumulation and ablation, as well as for example ice velocity. A large part of the data is transmitted by satellite near real-time to support ongoing applications, field activities and the planning of maintenance visits. The data have been essential for assessing the impact of climate change on land ice. The data are also crucial for calibration and validation of satellite-based observations and climate models (van As *et al.* 2014).

The current version of the GEUS AWS was developed in 2007 (sensors and tripod) and in 2008 (data logger, satellite data telemetry and power management) coinciding with the establishment of the Programme for the Monitoring of the Greenland ice sheet (PROMICE; Ahlstrøm *et al.* 2008) and the GlacioBasis Programme monitoring an ice cap in A.P. Olsen Land in North-East Greenland (APO; Fig. 1). In con-

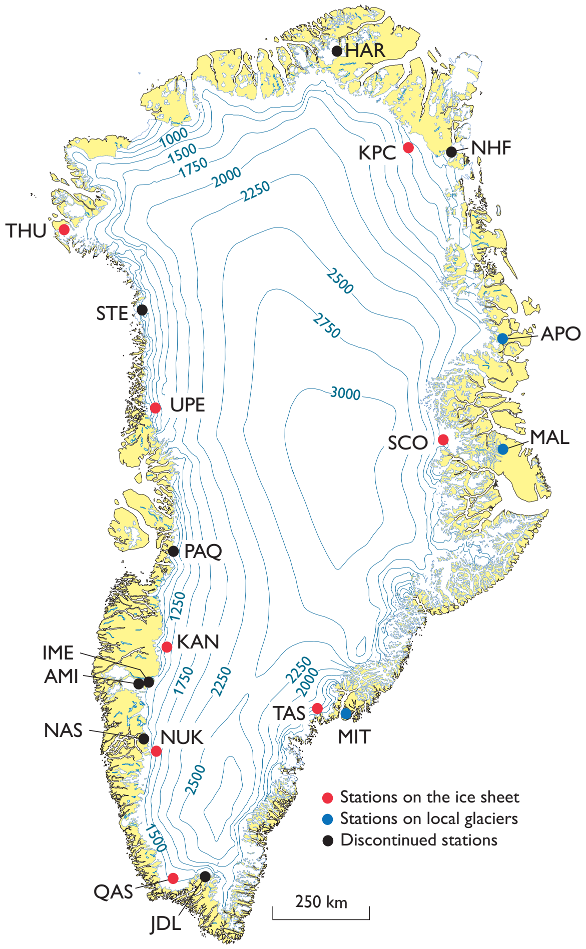

Fig. 1. Sites monitored by the Geological Survey of Denmark and Greenland with automatic weather stations. The currently active sites on the Greenland ice sheet (red dots) consist of transects with two or three stations at different elevations. QAS: Qassimiut (2000–). NUK: Qamanaarsuup Sermia, Nuuk (1979–1989, 2008–). KAN: Kangerlussuaq (2008–). UPE: Upernavik (2008–). THU: Tuto Ramp, Thule (2008–). KPC: Kronprins Christian Land (1993–1994, 2008–). SCO: Violin Gletscher near Scoresby Sund (2008–). TAS: Tasiilaq (2004–). Currently active sites on local glaciers (blue dots), with one to three AWS per site are APO: ice cap in A.P. Olsen Land (2008–). MAL: Malmbjerg (2008–). MIT: Mittivakkat glacier (1995–). Sites where GEUS had automatic weather stations in the past (black dots), some of which in cooperation with the former Greenland Technical Organisation: JDL: Nordbogletscher, Johan Dahl Land (1977–1983). AMI Amitsuloq Ice Cap (1981–1990). PAQ: Pakitsoq (1984–1987). NAS: Narsap Sermia (2003–2006). ISO: Isortuarsuup Tasia (1984–1987). NHF: Nioghalvfjerdsfjorden (1996–1997). HAR: Hare Gletscher (1994–1995). STE: Steenstrup Gletscher (2004–2008). IME: Imersuaq (1999–2002). STS: Storstrømmen (1989–1994).

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nection with consulting work, the first AWS with the new design (MAL; Fig. 1) was installed in 2008 for Quadra Mining Ltd., Vancouver, Canada (now KGHM International Ltd., Lubin, Poland) near the Malmbjerg molybdenum occurrence in Stauning Alper, central East Greenland (Citterio *et al.* 2009), followed in 2008 and 2009 by three more stations on the ice sheet in the Kangerlussuaq region (KAN, Fig. 1). These stations are part of the Greenland Analogue Project (GAP; van As *et al.* 2012) for SKB, the Swedish Nuclear Fuel and Waste Management Company (Stockholm, Sweden) and Posiva Oy (Olkiluoto, Eurajoki, Finland).

The GEUS AWS model in use now is a reliable tool that is adapted to the environmental and logistical conditions of polar regions. It has a proven record of more than 150 station-years of deployment in Greenland since its introduction in 2007–2008, and a success rate of *c.* 90% defined as the fraction of months with more than 80% valid air-temperature measurements over the total deployment time of the 25 stations in the field. The rest of this paper focuses on the technical aspects of the GEUS AWS, and provides an overview of its design and capabilities.

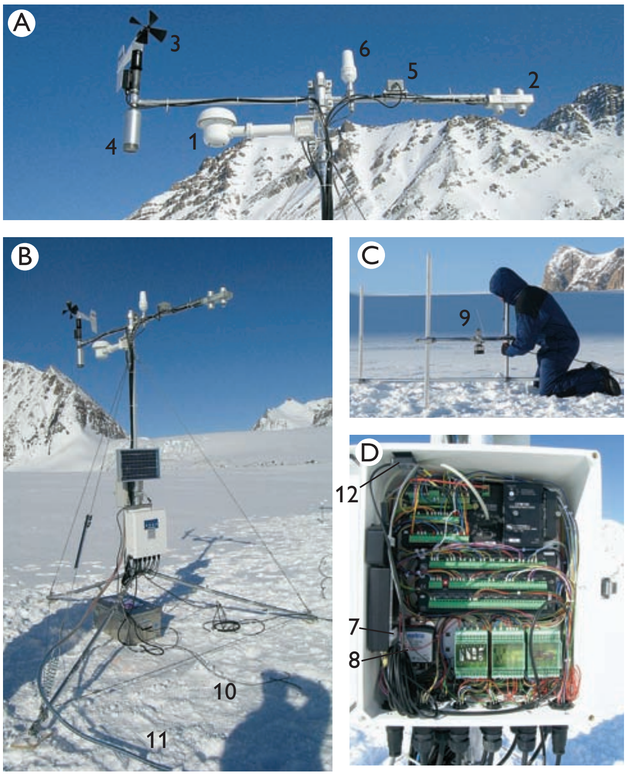

Fig. 2. Standard sensor suite of the automatic weather station on Arcturus Gletscher at the Malmbjerg molybdenum prospect. **A**: The main instrument boom. **B**: The tripod and the sites of the thermistor string and pressure-transducer assembly drilled into the ice. **C**: The sonic ranger- stake frame drilled into the ice. **D**: The inside of the data logger enclosure. The numbers refer to the list in Table 1.

Station requirements

The GEUS AWS is the fundamental component of a monitoring network which can include numerous stations, a satellite data link, and a receiving database where telemetry data are decoded and validated before further analysis and dissemination. The cost-effective AWS delivers timely research-quality data year-round from glacier ablation areas in remote locations. The AWS must therefore require little maintenance, with a target of maximum one visit per year. Power generation and battery capacity must be sufficient to operate through the polar night. Data quality must be assured by accurate measurement techniques including aspiration of radiation shields and tilt correction of (shortwave) radiometer measurements. The mechanical construction of the station must keep the sensors at a constant height above the ice surface, which can ablate more than 9 m of ice per year in South Greenland (van As *et al.* 2011), and the station must be able to survive burial in snow in the winter months. Timeliness of data availability and the assessment of station health demand satellite data telemetry both in summer and winter. To our knowledge, no other commercially available AWS satisfies all these requirements.

Sensors, data logger and telemetry

The GEUS AWS can be fitted with any sensor, but the standard AWS measures air temperature and humidity, wind speed and direction, atmospheric pressure, downward and reflected solar shortwave radiation, downward and upward longwave radiation, subsurface (ice) temperatures, snow depth, ice ablation, GPS position, as well as diagnostic parameters such as battery voltage and ventilator power consumption, and 2-axes station tilt necessary for correcting shortwave radiation measurements. Table 1 lists sensor types, their measurement heights and uncertainty as specified by the manufacturers.

The GEUS AWS is designed to minimise measurement errors where possible, for instance by actively aspirating the radiation shield inside which air-temperature and humidity sensors are located. Successful error detection and management increases with user experience and specialist knowledge.

Two of the sensors listed in Table 1 are designed and manufactured in-house at GEUS for use on ice: the 8-levels thermistor string and the pressure transducer assembly (PTA) that measure ice ablation (Fausto *et al.* 2012). The PTA works by relating decrease of bottom hydraulic pressure (corrected for atmospheric pressure), measured inside an antifreeze-mixture filled hose drilled into the ice, to surface

Table 1. Current sensors used on a standard GEUS automatic weather station

	Parameter and sensor height	Manufacturer, type and sensor accuracy
1.	Air temperature and relative humidity, 2.7 m	Rotronic MP102H with Pt100 and HC2-S3 probe (±0.1 K, ± 0.8% rh, at 23°C ± 5 K), housed in a RS12T aspirated shield
2.	Radiation (downward and reflected solar shortwave, downward and upward longwave; 2.9 m)	Kipp & Zonen CNR1 (uncertainty in daily totals < 10%) or CNR4 (uncertainty in daily totals < 5% shortwave, < 10% longwave)
3.	Wind speed and direction, 3.1 m	R.M. Young 05103-5 (± 0.3 ms^{-1} or 1%, ± 3°, non-riming conditions)
4.	Snow depth	Campbell Scientific SR50 or SR50A (± 1 cm or 0.4%)
5.	2-axes radiometer tilt	HL Planar NS-25/E2 in GEUS assembly (± 0.2°)
6.	Iridium satellite antenna	Iridium AT1621-142 quad-helix
7.	Iridium SBD modem	u-blox NEO module
7.	Iridium SBD modem	NAL Research SBD-9601 or SBD-9602
8.	Atmospheric pressure	Setra model 278 (± 2.5 hPa, at –40 to 60°C)
9.	Ice ablation and snow depth	Campbell Scientific SR50 or SR50A (± 1 cm or 0.4%)
10.	Subsurface temperature profile	GEUS thermistor string with 8 RS Components thermistors 151-243 (± 0.2°C, at 0°C)
11.	Ice ablation	GEUS PTA with Ørum & Jensen Elektronik NT1400 or NT1700 (± 2.5 cm)
12.	GPS antenna	Trimble P/N 56237-40 active ceramic patch

The numbers refer to Fig. 2 where the positions of the sensors on an automatic weather station are shown.The heights of the sensors above the surface are indicative. The accurate heights are measured before and after every maintenance visit.

lowering due to ice ablation. Both the PTA and the thermistor string can easily be interfaced to most data loggers.

All analog and digital sensors are connected to a Campbell CR1000 data logger housed in a watertight enclosure together with a Campbell AM16/32A analog multiplexer and supporting circuitry. The logger is programmed to record in 10-minute cycles throughout the year. The only exception is the GPS, which is not needed at such a high rate and is activated less frequently in order to economise power. The Campbell CR1000 data logger is an established platform that is widely used in polar climates both in the Arctic and in Antarctica (Lazzara *et al.* 2012). The multiplexer is configured to support half-bridge measurement of thermistors from up to four 8-level thermistor strings (only one is normally used), in addition to 32 single-ended or 16 differential analog measurements (only six of each type are normally used), providing large flexibility for customised sensor suites.

The main local data storage is a removable flashcard rated for operation over extended temperature ranges. For reference, a 256 MB card will log in excess of 7 years of 10-minute records. To provide redundancy of data storage, the internal logger memory is configured to store 1-hour average records and can hold in excess of one year of data as a backup for the flashcard. Data can be retrieved during on-site maintenance by swapping the flashcard or downloading its content to a laptop. The robustness of the system is illustrated in Fig. 3 by an uninterrupted 2008–2015 time series from the APO_M station in North-East Greenland, the first AWS built entirely according to the current GEUS design. After seven years in the field, this station still employs the original electronics, telemetry, battery and tripod hardware although sensors have been periodically replaced according to a scheduled recalibration plan.

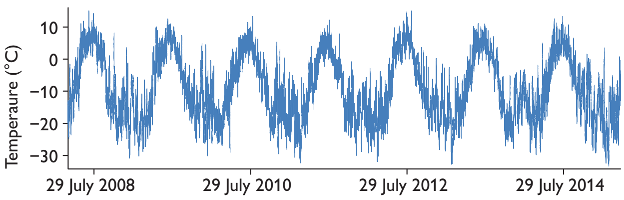

Fig. 3. An example of 10-minute observations of air temperatures from 2008 to 2015 from the APO_M station on an ice cap in A.P. Olsen Land in North-East Greenland.

Satellite data telemetry can transmit up to 340 bytes per message through the Iridium short burst of data (SBD) service. The program running on the CR1000 data logger implements a full software handshake with the transmitter to ensure that a satellite is in view and that data are correctly transferred from the logger to the transmitter and the Iridium satellite. If no acknowledgement of successful transmission is received from the satellite, the data logger will retry the transmission once, or queue the unsent message for delivery at a later time, depending on Iridium service availability. This mode of operation ensures a low rate of message loss and relatively low power consumption by avoiding unnecessary transmission attempts. The stations binary-encode data before transmission, reducing data transmission costs by about 2/3. Further transmission costs can be saved by transmitting the less transient variables at longer intervals.

Power

The long polar night and low temperatures exert a strong influence on the AWS design. The AWS operates on solar power and rechargeable sealed lead-acid batteries for a nominal total of 112 Ah at 12 V. The power system is composed of the main unregulated 12 V power rail permanently supplying the data logger directly from the batteries, two 12 V unregulated rails controlled by software through two external solid-state switches, and one switched 5 V regulated rail under direct data logger control. This arrangement allows independent powering up of the radiation shield aspirator fan, the GPS and satellite transmitter, the 5 V loads of the sonic rangers, temperature and humidity sensors, tilt meter and multiplexer. A single 10 W solar panel is wired to the main 12 V rail through a power Schottky diode to prevent that the solar panel drains the battery during the winter months, and to eliminate the need for a charge regulator, which occasionally failed in previous AWS designs.

A software-controlled low-power mode is activated when battery voltage under load falls below a configurable threshold (set to 11.5 V), which is never reached in normal circumstances. In low-power mode, operation continues almost as normal, but the most power-demanding functions (aspiration fan, satellite telemetry and GPS) are deactivated. The low-power mode is exited once solar charging brings the battery sufficiently above the voltage threshold. The software can be configured for polar day and night operation, for instance to reduce data transmission rates during winter. The typical monthly power requirements of a GEUS AWS as configured for PROMICE is 17 Ah in summer, 11 Ah in winter and 1.3 Ah in low-power mode.

Tripod and sonic ranger frame

The tripod is constructed from 1″ and 1.5″ aluminium tubes with steel wires connecting legs and mast in a tetrahedral structure for a stable free-floating tripod. Most of the sensors are fixed to a horizontal boom at *c.* 2.9 m above surface. The battery box, which weighs *c.* 50 kg, is suspended under the mast to improve station stability by increasing the AWS mass and lowering the centre of gravity. The tripod can be folded and transported in a small helicopter. During maintenance visits, which normally take 3–4 hours and include replacements of sensors due for recalibration, re-drilling of sensors and occasional repairs, the tripod can be easily tilted so that it does not have to be disassembled. The sonic ranger frame is also built from 1″ aluminium tubes, and its three vertical legs are drilled into the ice a few metres away from the AWS tripod.

Concluding remarks

The GEUS AWS has been developed, produced and deployed operationally by GEUS, and supplied to partners within Denmark and abroad. It is a proven solution for a wide range of basic and applied glaciological research in Arctic and alpine settings and is available through research collaborations or commercial sale. The standard design can accommodate significant expansion of the sensor suite. The GEUS AWS is readily available and supported as a stand-alone or as a component of wider services including field deployment, maintenance, training and data management and analysis.

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