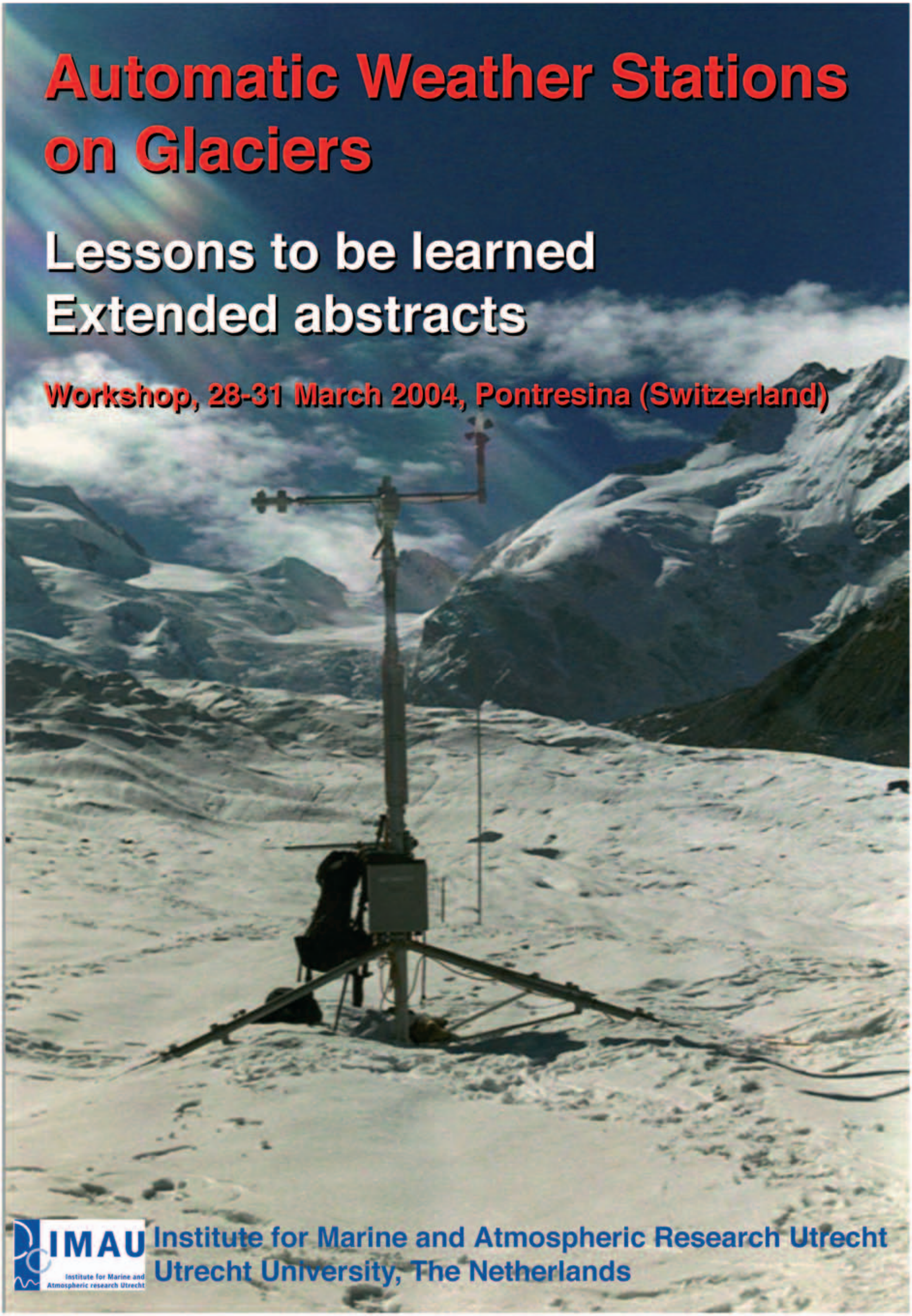
# Automatic Weather Stations on Glaciers

## Lessons to be learned
## Extended abstracts

**Workshop, 28-31 March 2004, Pontresina (Switzerland)**



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## Extended abstracts

## Workshop, 28-31 March 2004, Pontresina (Switzerland)

## Organised by J. Oerlemans and C.H. Tijm-Reijmer

Institute for Marine and Atmospheric Research Utrecht
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**Photo:** The Morteratsch glacier. (Photo: Carleen Tijm-Reijmer)

# PREFACE

During the last 10 years or so the number of automatic weather stations (AWS) deployed on glaciers has increased strongly. It has been realized by many research groups that meteorological data are essential for the validation of mass-balance models, meteorological models (regional/mesoscale) and satellite products.

A better understanding of glacier-climate interaction will require more extensive and more complete data sets from AWS. Apart from the measurements of standard meteorological quantities, there is a need for measuring automatically variables that are directly related to components of the mass budget (e.g. characteristics of the snowpack), or that are required to handle satellite data (e.g. reflectivity in spectral bands). Therefore AWS for glacier research should be developed further, in spite of the many problems that are encountered (power supply, unstable service, riming and icing, accessibility, tourists, etc.).

It appeared to us that people working with AWS could learn a lot from each other. After an inquiry through Cryolist it became clear that many liked the idea of having a workshop. And so it happened with a bit of support from my Spinoza-grant. Thirty-five people gathered under a deep-blue sky in Pontresina, Switzerland, 28-31 March 2004. In the end we all agreed that the mix of short presentations and discussions, and not at least the excursion to the Morteratschgletscher in fabulous conditions, was very useful and inspiring. And we also agreed that it would be nice to have a document that provides an overview of problems and potential solutions related to the operation of AWS on glaciers. Jason Box, Phill Anderson and Michiel van den Broeke volunteered, and their contribution can be found in this little book.

I hope that this collection of extended abstracts will be useful to newcomers and will also remind the participants of the wonderful days we had.

Finally I want to thank my co-convenor Carleen Tijm-Reijmer for help in organizing the workshop, and for the great effort she made to edit this document.

Hans Oerlemans
convenor

# PROGRAM

**Sunday 28**

- 14:00 – 14:15 Welcome *Johannes Oerlemans*
- 14:15 – 14:40 Operating the AWS at Western Canada glacier sites. *Scott Munro*
- 14:40 – 15:05 High-elevation weather stations on glaciers in the Tropics and the High Arctic. *Doug Hardy*
- 15:05 – 15:30 AWS in the ablation zones of glaciers. *Johannes Oerlemans*

15:30 – 16:00 Coffee break

- 16:00 – 16:25 Glacier margin micro-meteorology and its importance for weather station placement. *Andy Bliss*
- 16:25 – 16:50 How useful are surface radiation balance observations from automatic weather stations in Antarctica? *Michiel van den Broeke*
- 16:50 – 17:15 Measuring humidity at low temperatures. *Carleen Reijmer*
- 17:15 – 17:40 Meteorological and snow measurements on a mountain site in tropical Andes Data Set Build-up for Energy Balance Modeling. *Yves Lejeune*
- 17:40 – 18:00 An AWS mounting device which mechanically adjusts itself to changing glacier surface conditions. *Georg Kaser*

**Monday 29**

- 08:30 – 08:55 The AWS network on Greenland over the past 14 years. *Konrad Steffen*
- 08:55 – 09:20 Lessons of Greenland ice sheet and tropical ice cap AWS maintenance. *Jason Box*
- 09:20 – 09:45 Greenland Climate Network (GC-Net): Future Measurements: Eddy flux measurements under severe conditions. *Nicolas Cullen*
- 09:45 – 10:10 Measuring turbulent heat fluxes on Morteratschgletscher, Switzerland, with a sonic anemometer. *Lisette Klok*

10:10 – 10:35 Coffee break

- 10:35 – 11:00 Calculating and validating the surface energy balance in the katabatic wind zone of Antarctica, using single-level AWS data. *Michiel van den Broeke*
- 11:00 – 11:25 On the performace of unaspirated, plate-shielded thermometer screens. *Friedriech Obleiter*
- 11:25 – 11:50 Air temperature measurements in the glacier environment *Regine Hock*
- 11:50 – 12:15 Correction of air temperature data measured by naturally ventilated sensors over snow and ice. *Dieter Scherer*

12:15 LUNCH on Diavolezza

- 16:45 – 17:10 Using automatic weather stations on the ice caps of Canadian High Artic islands, experiences and problems from an extreme environment. *Claude Labine*
- 17:10 – 17:35 The use of free wave radios for telemetry of weather data from 2500 m on McCall Glacier, Arctic Alaska. *Matt Nolan*
- 17:35 – 18:00 AWS on a penitente-covered glacier of the High Central Andes, Chile. *Javier Corripio*
- 18:00 – 18:25 Meteorological studies on the Morteratschgletscher, Switzerland. *Johannes Oerlemans*

### Tuesday 30

Excursion to the IMAU weather station on the Morteratschgletscher.

- 20:30 – 21:00 Evening lecture *Felix Keller*

### Wednesday 31 March 2004

- 09:00 – 09:25 Barking Spider - An Open AWS Platform *Chris Boucher*
- 09:25 – 09:50 Automatic snow and weather stations in the Swiss Alps *Hansueli Gubler*
- 09:50 – 10:15 Portable AWS running in remote high areas in the tropical Andes of Bolivia, Peru, Ecuador. *Patrick Wagnon*

10:15 – 10:40 Coffee break

- 10:40 – 11:05 Experiences with the new hydro-meteorological station “Vernagtbach”. *Ludwig Braun*
- 11:05 – 11:30 Aspects of logistics and power consumption for the operation of AWS in harsh environment in Southern Patagonia. *Christoph Schneider*
- 11:30 – 11:55 Antarctic the largest glacier of them all. *Steve Colwell*
- 11:55 – 12:15 Conclusion *J. Oerlemans*

**Photo:** The Rondo convention centre in Pontresina, Switzerland (Photo: Jason Box)

# LIST OF PARTICIPANTS

**Photo:** The participants behind the IMAU weather station on the Morteratsch glacier. (Photo: Carleen Tijm-Reijmer)

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**Photo:** Lunch on Diavolezza. (Photo: Carleen Tijm-Reijmer)

**Photo:** Walking to the IMAU AWS. (Photo: Carleen Tijm-Reijmer)

**Photo:** Skiing to the IMAU AWS. (Photo: Carleen Tijm-Reijmer)

**Photo:** The IMAU AWS on the Morteratsch glacier. (Photo: Dieter Scherer)

# LESSONS TO BE LEARNED

JASON E. BOX, PHILL S. ANDERSON AND MICHIEL R. VAN DEN BROEKE

## CONTENTS

## 1. Introduction

Automatic Weather Stations (AWSs) have been deployed over a wide variety of glaciated surfaces, for example, on: continental ice sheets; valley glaciers; sea ice; and ice bergs; and have a variety of applications, including: climate variability assessment; in support of operational weather forecasting; model validation and in avalanche information support. AWS applications share a common challenge of obtaining continuous and reliable measurements both unattended and often in extreme environments. AWS have facilitated growth in the branch of *glaciometerology*. The 1st AWS On Glaciers Workshop, hosted by J. Oerlemans of The Institute for Marine and Atmospheric Research Utrecht, Netherlands (IMAU) in Pontresina Switzerland, March 27-30th, 2004 brought together the international AWS community to share practical experience gained since the 1980s when AWS applications really gained momentum. The following text collects major lessons of this group's experience to provide tips for increased success in reliable data acquisition from future AWS operations on glaciers.

Common difficulties facing AWS are:
- Rime and hoar accumulation can interrupt and bias measurements.
- Solar radiation shielding of temperature and humidity measurements.
- Melting and/or accumulation affect instrument height and leveling.
- Mast stability/leaning and instrument failure due to extreme weather conditions.
- Limited number of visits owing to remote operation.
- High latitude sites have particular power and low temperature challenges.
- Short time-on-site does not allow extensive procedures.

The following discussion offers insight from past efforts to meet these challenges. The report is arranged by topic and is intended as a kind of fact sheet for consideration to boost success in AWS data acquisition.

## 2. Philosophy of Design

In most cases, an AWS deployed on a glacier is costly to install, difficult to visit, and must provide trustworthy data, otherwise the cost and effort seems unjustified. Often a multi year record is required, such as assessing climate variability or developing a climatological baseline, e.g. for an ice core site. Often, data are required real time. This has been facilitated by satellite, radio telemetry and recently by exploitation of proliferating mobile telecommunication networks. In remote applications, aircraft operation can rely on this information. Mean time between failures (MTBF) of more than five times the mean time between visits is a reasonable planning strategy. For many stations this demands MTBF > 5 years! To achieve this level of reliability, the station must be:

- Free of design flaws, be they software bugs, electrical wiring errors, or mechanical miscalculations.
- Robust, to withstand icing, freeze/thaw, high winds, low temperatures, ice creep, extreme thermal cycling, etc.

Invariably, the pursuit of a robust system has lead investigators to concentrate on *success in simplicity*. Although apparently obvious, simplicity is easily overlooked by engineers keen to make "Can Do" systems, that is, just because modern electronics and software *can* allow clever and complex features, they are not just unnecessary, but can reduce the system reliability. Experience has shown that the number of ways AWSs can fail in an *unexpected* way increases exponentially with complexity. Therefore, it is arguable that it is better to get a smaller high quality data set than a larger set of data with questionable accuracy. Useful considerations include:

- If site visits are planned, is telemetry really needed?
  - Exceptions include if instrument status is needed for planning; near real time capabilities are desirable; and there is a potential of not returning.
- AWS power supplies provide at least 2 x overkill as a rule of thumb, owing to reduced battery performance in the cold. Hence, if 6 months of battery life is needed, success is better ensured by doubling up the batteries to give 12 months, in which case, if annual visits are made, a solar panel and regulator may even be phased out.
- Log raw data, not data with multipliers and calibrations applied in-line. If calibration techniques change, the raw data will need to be available. Furthermore, less calculations reduce power requirements.
- Logging should be as simple as possible, and then tested, tested, tested. Often, it will not be until after years of field deployments that the system runs reliably.

### *2.1 Site Maintenance Considerations*

Competing factors exist in terms of success in AWS data acquisition and what is done during site visits.

- The *time on site* if limited may rush a technician and result in forgotten or incomplete maintenance tasks. Competing against sufficient time are a number of factors often not controllable, such as limited aircraft ground stop time, daylight, and weather difficulties. It is therefore clear to maximize and optimize work prior to field deployment to take advantage of the relative comfort of the off glacier environments (e.g. labs, warehouses, or just lower elevations) and once on site, to follow a prioritized maintenance, in light of the time constraint.
- Time needed to perform maintenance increase with decreasing temperature and as wind speed and altitude increase.
- Often, the logistical cost to visit AWS on glaciers meets or far exceeds the cost of *spare equipment*. Therefore, in cases when no communications with the AWS are available to inform what replacement instruments to bring, it is reasonable to come prepared to replace any AWS component, even AWS platform components. Furthermore, experience has also shown that AWS components may be broken during maintenance and therefore spares are commonly needed.
- Perhaps the most interesting paradox is that maintenance is a source of discontinuities in long term records. Therefore, when on site, exercise extreme caution and change as little as possible.

### *2.2 Consistency*

When running more than one AWS, it makes sense to be consistent. Experience has shown that using different instruments at different sites, can lead to data loss given different software to keep track of or more work and uncertainty associated with the need for inter-calibration of changed instruments. Items to be consistent with are:

- Instruments
- Program
- Hardware
- Maintenance protocol

### *2.3 Tips for Success*

- Change as little as possible. In other words: "*if it ain't broken, don't fix it*"
- If batteries are buried in the snow, include a small backup battery in enclosure or fixed to AWS platform. Thus, if the remote power cable is interrupted, data logging continues.
- Put telemetry power on different batteries, but with shared ground.
- Inexpensive tools and mounting hardware are more likely to fail or simply not do what they are designed for. This also refers to instruments. Usually unless you are lucky or uncommonly clever, "You get what you pay for"

### *2.4 Accumulation Zone Issues*

Extend accumulation zone sites in autumn so that profile instruments may be near the surface where the gradients (the signal) is largest for the summer when turbulent heat fluxes are often largest. Plan ahead, knowing something about accumulation rate, that the tower will survive abnormally high accumulation.

## 3. Measurements

A discussion of problems encountered for the most frequently required variables in glaciometerology follows. The variables include:

- air and surface temperature
- wind speed and direction
- snow/ice accumulation and ablation
- humidity
- snow/ice conductive heat flux
- shortwave and terrestrial radiation fluxes

### *3.1 Temperature*

Under ideal circumstances, air temperature measurements may be obtained with errors corresponding to accuracy specified by the instrument manufacturer, e.g. ±0.1 K RMS error. However, over glaciated surfaces, the accuracy of temperature measurements are often degraded owing to the following factors:

- Solar and infrared radiation.

- Shields and instruments heat up from solar radiation absorption and emit excessive infrared radiation. These factors contribute to overheating errors that can exceed 10 K.
- Upward (reflected) shortwave radiation from the high albedo surface contributes to excessive shield absorption and also shortwave diffuse radiation absorption by the instrument if exposed in line of sight from below.
- There is some debate as to what single factor is most important. Suspects include direct-beam visible radiation, surface albedo, and actinic flux.

- Power limitations commonly preclude continual forced aspiration.
- If continual forced aspiration is made, sublimation of ice formed or sucked in the shield can significantly depress the observed temperature, giving an ice-bulb or wet-bulb effect. The opposite effect of heating is feasible in conditions of condensation or hoar/rime growth on sensors.
- Ice accumulation can insulate the sensor from expected normal air flow
- Self ventilating shields - Although radiation shields are now available with their own solar powered ventilation, it may be impossible to be certain of the ventilation rate without monitoring ventilation speed (motor voltage), considering that the ventilator motor can degrade, i.e. slow down, and fail at an otherwise unknown time.

*3.1.1 Insolation*

Invariably, "naturally" aspirated radiation shields are used, as power for active aspiration has commonly been unavailable. Most radiation shields are designed to protect the sensor from down-welling shortwave radiation, and assume that the ground has a low albedo. However, snow can reflect more than 90% of this radiation, and when viewed from below, to restate, some sensors within the shields are actually visible from below.

Incident shortwave radiation can affect the sensor reading in two ways. Firstly, by reflecting into the shield and hitting the sensor directly. Secondly, by being absorbed inside the shield, and heating the air inside the shield and the shield itself. As yet, there are no models of shield response to both these effects, although D. Scherer (see report in this issue) makes a good attempt to correct overheating using an instrument independent physically based model. Some shields have black inner faces, which will eliminate direct sensor heating, but will exacerbate "shield heating". It is also clear that a shield made of perfect white material will actually have *no* shielding effect if exposed to perfectly isotropic diffuse shortwave radiation, because the diffuse shortwave will eventually reach the sensor! This argues for sensors colored as white as possible. A second counterintuitive effect is that diffuse shortwave radiation has a higher *actinic* flux (photons per cubic meter) than the equivalent direct radiation (as measured by the magnitude of the downward flux). This is due to the photons cris-crossing the same volume, an effect well documented in the air chemistry literature where the actinic flux dominates atmospheric photochemistry, not the more familiar "meteorological" directional radiation fluxes, i.e. Watts passing though a horizontal unit area. It is the local *actinic* flux that governs the sensor heating. This must be born in mind over snow, as shortwave radiation reflected from snow is highly diffuse, and hence snow cover would more than double the actinic flux acting on an unshielded sensor.

It is plain that no matter how the shield is designed, the *sensor* should be white. We suggest even sensors within aspirated shields (e.g. the standard Vaisala HMP45 inside the Young aspirated "umbrella" shield (not the plated shield)) should be painted to reduce reflected insolation errors. However, a robust paint must be used, to withstand brittle effects at low temperatures, UV radiation, and adhering to a smooth plastic. Paint does not adhere well, for example, to Teflon, a common thermocouple cable shielding material.

#### *3.1.2 Dual Function Shields*

A secondary solution to insolation error is to add solar powered aspiration to a naturally ventilated shield (or have two shields, one aspirated, but solar powered). Given that insolation errors are worst when the sun is shining, solar power is available when aspiration is most needed. Such shields are under comparison at Halley (a standard Young natural ventilation shield with added aspiration) and the commercial Davos system. IMAU and BAS have independently developed a computer-fan aspirated shield. Actively aspirated shields offer an obvious solution, but for confidence in results, need to be evaluated under true snow conditions, in which case, persistent overheating errors may be of little surprise.

#### *3.1.3 Remotely sensed temperature: The Future?*

Moderately thick fine wire thermocouples (0.003”) are superior in measuring air temperature (passively, i.e. no aspiration power and fan problems) than any kind of ‘naturally’ or ‘actively’ aspirated shield. Finewires have been observed to break from impact of snowflakes and blowing snow and from snow-creep and freeze thaw. Another alternative to the shield albatross is sonic or otherwise remotely sensed temperature, e.g. CSAT3D sonic temperature, IR thermometers. This technique requires more validation. Apart from surface temperature derived radiometrically, one will always need to measure air temperature at least at one level.

#### *3.1.4 A Shield Standard?*

Given that shield designs change, there is no apparent standard and it is best not to recommend a specific design, but to recommend that each investigator be sure to assess the limitations of whatever shield selected based on an experiment made in the glacier environment with reliable ventilated shields, fine wire thermocouples, or perhaps even sonic temperature.

### *3.2 Wind Speed and Direction*

Power constraints for remote AWS have meant that winds are invariably measured with cup anemometers + wind vanes, or the combined propeller and vane (propvane). Other methods (acoustic, pitot) present problematic power requirements. The most significant problem with measuring winds at glacier AWS sites, in low power systems, is *rime ice* accumulation, which acts to reduce the measured wind speed, and prevent the vane from turning. Scale is an issue, in that 1 cm of rime will obviously affect a small cup set more than a large cup set. Similarly, a large vane with a large turning moment will remain free to rotate, or break free of the rime sooner than a small vane. Therefore, bigger appears to be better, apart from the disadvantage of increased over-speeding error with bigger cups. The propeller vane is also better able to cope with rime accumulation than the cup. The propeller itself is nearly frictionless and cuts a near perfect helix through the air as it turns. Only the leading edge of the propeller is passing through the air, and hence there is only a small area that is being impacted by any cloud/fog droplets (and hence accumulating rime). The cup anemometer is a much less desirable design, as it is constantly turning with the back of the cup in opposition to the wind, and the front of the cup (through the drag on the other cups) traveling slower than the wind. In this design, rime accumulates more rapidly than on a propeller. In heavy riming both propvane/cup+vane will eventually stall.

### *3.3 Snow Depth*

Acoustic surface height indicators are susceptible to the following problems.

- Instrument failure from freeze-thaw delamination of the acoustic membrane.
- Membrane obstruction by snow/rime.
- Erroneous height from reflection from a dense drifting snow layer.
- Raw data should be collected and speed of sound correction applied in post processing. Reason: temperature measure can foul surface height data.
- Snow drift tower wakes and moats can be problematic. Therefore, instruments should be oriented upwind.
- H. Gubler has installed a cone on the SR-50 to protect the aperture from snow packing in.
- Membrane failure rate has been observed to increase with age. Therefore, regular replacement of the acoustic membrane should be considered each year.
- It has been noted that the proximity of open sea significantly reduces membrane lifetime. On Iceland, where the sea is never far away and the air carries a lot of salt, membranes last as short as 1 year; in Antarctica, lifetimes as long as 5 years have been recorded without a single problem.

### *3.4 Humidity*

Vapor pressure, dew point, mixing ratio etc. are commonly derived from capacitive (occasionally resistive) humidity sensors when deployed on AWS. Other sensors, notably the cooled mirror hygrometer, are more accurate but require human interaction (occasional cleaning of ice lenses on mirror) and much more power.

The sensor itself has many of the problems associated with the measurement of temperature, especially as the sensor itself must be in both hygrometric *and thermal* equilibrium with the ambient air. Most sensor packages include a temperature sensor adjacent to the active capacitive humidity sensor. In the HMP45, the 100 ohm PRT air temperature sensor is completely electrically isolated from the humidity electronics. There is usually a secondary, cruder temperature sensor within the instrument housing, used to add correction to the humidity value. A number of points should be noted to understand the problems with common humidity instruments.

- The capacitive and resistive (and hair!) active components respond to a first approximation to RH with respect to water ($RH_{water}$). This is before any correction is added by the instrument.

- The Goff-Gratch equations (Sargent 1980) or approximations thereof are needed to calculate actual RH relative to saturation over ice ($RH_{ice}$), see Anderson (1994).
- The linearity of the active sensor is poor above 98% $RH_{ice}$.
- When the ambient air is saturated or super saturated, the porous sensors become clogged, and takes minutes or hours to recover given drier air. This is even after the apparent surface ice, which may be coating the sensor, has sublimated.

Many commercial sensors have a slight residual non-linearity at low temperatures, temperatures below the manufacturers specifications, but the instruments often still work well, and this non-linearity can be corrected following Anderson (1994). There is some uncertainty as to whether only a simple gain correction is needed, and not a gain plus offset. This requires some further study, and comparisons with chilled mirror devices.

The main difficulty with using the hydroactive sensor is the inability to measure super-saturation, and the long recovery time following clogging. See Anderson (1995) for a description of this effect. Data quality can be judged visually from RH time series, especially in drainage or katabatic regions: the reading will remain clipped and constant at 100% $RH_{ice}$ and then suddenly dip to more believable drier values.

We suggest that where possible, the RH sensor should also be painted white, but this is not directly feasible as the paint would prevent vapor transport into the hydroactive material. Most RH instruments included a protective cap and the cap at least should be painted white. Within the protective cap there is often a permeable membrane: obviously this should not be painted!

### *3.5 Snow/Ice Conductive Heat Flux*

Unlike soil heat flux, where a standard flux plate will give a suitably accurate reading, snow and ice heat flux suffers from the ever changing level of the surface and solar radiation absorption. Accumulation buries any sensor, ablation exposes it again, melt water advects heat vertically and horizontally, whilst the latent heat of melting itself acts as an additional flux with its own difficulties in autonomous measurement. Solar radiation absorption is mitigated using thin wire thermocouples or extrapolating deeper temperatures to shallower layers and comparing the estimated surface temperature with accurate IR thermometry (Van den Broeke et al. 2004).

In polar regions where the snow remains dry (but may still ablate), the situation is somewhat easier than described above. The conductive heat flux may be estimated from thermal gradients at the surface, and estimates (from occasional measurements) of snow density. The thermal gradient themselves are either estimated from temperature probe arrays, or derived from the time series of the snow surface temperature (see below). Snow temperature probe arrays come in three varieties.

- Robust steel sheathed temperature sensors on a rigid pole, i.e., ‘Magic Sticks’.
- Temperature sensors along a cable bundle.
- Non-rigid sensors which move with the snow compaction.

All suffer from the requirement for sensors to be near the surface at all phases of the accumulation/ablation processes, with a small separation (c. 10 cm). The cost and complexity of logging can be formidable for accumulation/ablation regimes > 2 m. The bonus is that the snow level itself can be estimated from variance differences, or inversion techniques, which may augment or check on the snow depth gauge readings. Also, the presence of liquid water is readily detected by measured values constant heat 0°C.

Robust steel sheathed sensors give accurate temperatures, and do not appear to suffer from conductive losses down the pole given a pole of light wood, and that the whole apparatus is painted white. Near surface heating and cavitation (air gaps around the probe) are occasionally problematic in summer.

The cabled sensor is most often used for snow chemistry work. Compression of the cable is unknown, and the accuracy of the data has not been tested as comprehensively as the solid pole array.

Laying sensors unsupported within the snow is suitable for ablation sites, but suffers from the inability to cope with accumulation: in order to be at the correct separation once snow has covered the sensors, they need some level of support whilst in the air awaiting burial. In addition, the uncertainty in probe separation as the snow compacts causes errors in the calculation of the heat flux.

Given these difficulties, an alternative to measuring the snow temperature profile directly is by Fourier, Laplace or Crank-Nicholson schemes. The snow is assumed to be a pure 1D semi-infinite thermally diffusive medium. This approximation is good for non-melting snow. In this situation, the snow profile is governed solely by the history of the surface temperature and the thermal diffusivity of the firn. This latter can be measured by one extra sub-surface probe, or estimated from previous measurements. For a diurnal cycle in the snow surface temperature, the Fourier transform of the heat equation is most suitable (i.e. the polar summer), whereas where synoptic / katabatic events dominate (where there is no dominate mode in the frequency), the Laplace transform is appropriate. The technique is well documented in many engineering texts.

The snow temperature profile may also be modeled directly, using the Crank-Nicholson scheme for the 1D diffusion equation. This is somewhat more computationally demanding but this may prove of small consequence given the power of modern PCs.

### *3.6 Shortwave and Longwave Radiation Fluxes (adapted from Van den Broeke et al, 2004)*

For a long time, radiation measurements from polar AWS have been regarded as of little use due to problems of a poor cosine response under high zenith angles, low temperature malfunction and/or riming of the sensor windows. This has changed with the advent of low cost, robust sensors like the Kipp and Zonen CNR1 that incorporate four individual sensors for the upward and downward shortwave and longwave radiation fluxes. These sensors have been operated for about 8 years now on glacier AWS in the Alps, Norway, Iceland, Greenland and Antarctica. They seem to perform well when compared on-site to higher-standard sensors. The big advantage of this sensor is that it measures all components individually, so that corrections may be applied to individual radiation fluxes. Linearity seems to become poorer below -45 °C but this has to be investigated closer. Although the sensors include a heating option (several Watts), this is probably not feasible for low power AWS, nor is ventilation.

*3.6.1 Shortwave radiation fluxes*
A shortwave sensor with a single dome is advantageous because it is much less susceptible to riming; when the sun shines, the black sensor plate heats up considerably and therewith also the glass dome, which prevents rime formation. A single domed shortwave sensor thus should always be the first choice, even though this will allow some convection. Note that the downward facing shortwave sensor is much less prone to measurement error. It thermally equilibrates with the relatively warm surface (warm compared to the clear atmosphere) so that riming is less likely to occur on down-looking pyranometers. Down-looking pyranometers also receives isotropic radiation, making them much less susceptible to errors associated with a poor cosine response and sensor tilt. When one uses 24-h running integrated values of both sensors to calculate albedo (therewith minimizing cosine response errors) in combination with the instantaneous signal of the downward facing sensor, much better estimates of instantaneous net shortwave radiation are obtained compared to simply subtracting the reflected from the incoming signal, especially over highly reflective surfaces when both fluxes are of similar magnitude. Another advantage of this method is that spuriously high/low albedo values may indicate icing problems and assures an easy quality check. A disadvantage of this method is that the daily albedo cycle is eliminated. This can be partly remedied by adding a theoretical daily cycle.

*3.6.2 Longwave radiation fluxes*
The measurement of longwave radiation fluxes is important, as longwave radiation play a major role in the energy balance of the polar regions, where most of the shortwave radiation is reflected at the surface. It is therefore desirable to measure the longwave fluxes directly rather then obtaining them from measurement of allwave radiation from which the shortwave fluxes is subtracted. Because net radiation is usually small over ice, this procedure leads to large errors. Another advantage of the direct measurement of upwelling longwave radiation is that one has a reasonable estimate of surface temperature (assuming unit surface emissivity). Having a value for surface temperature is advantageous to calculate temperature gradients in the air and the snow pack, facilitating heat flux calculations. It also provides a good estimate of surface moisture concentration (assuming the snow/ice surface to be saturated), an important parameter for sublimation calculations.

Longwave radiation measurements suffer from a window-heating offset caused by absorption of solar radiation by the wavelength selective filter. This error is hard to detect but can be minimized by ventilation, if power allows. Over highly reflective surfaces, window heating will tend to offset in the calculation of net longwave radiation when both longwave fluxes are used. Another major problem is icing of the sensor windows. Rime completely obstructs the passage of longwave radiation. If sensor design is a thermopile, i.e. to measure the temperature difference between the sensor body and the object it looks at, the signal will go to zero. As such, this error is easy to detect, but hard to solve in postprocessing. One may try to design a parameterization of net longwave radiation with temperature as predicting variable, based on data collected from non-riming episodes. Experience from Antarctica has learned that sensors operated in katabatic wind zones are much less prone to icing than those operated o the flat coastal ice shelves or in the interior; a probable explanation is that the adiabatically heated air is always sub-saturated, which maintains a constant sublimation even in mid-winter.

## 4. Platforms and Power Systems

### *4.1 Masts*

A variety of instrument platforms have been used successfully. The main instrument platform remains erect using structures including (for lack of better terms):

- monopods (e.g. GC-Net)
- tripods (e.g. GLACIOCLIM)
- quadopods (e.g. IMAU)
- light weight simple guyed pole masts (BAS upAWS, BAS LPM)
- lattice masts (e.g. US Antarctic AWS)

*Monpods* – ablation zone experience in Greenland (i.e. GC-Net) has shown that to minimize tower leaning, monopods must be inserted to a depth at least double the anticipated ablation, otherwise, one may expect thermal conduction down the mast to cause tower leaning even if as much as 2 m of the mast remains in ice. It may be that a thermal conduction insulator, such as from carbon fiber, may reduce thermal induced leaning, however, this has not been proven to be of sufficient strength to attempt operationally. To minimize maintenance, deeper insertions can prepare the monopod to survive multiple years.

*Tripods* – tripods are perhaps the most common AWS platform, as they are commercially available from such vendors as Campbell Scientific. Steel tripods, though strong, are often not desired for remote applications owing to their excessive weight. Aluminum versions are commonly used.

*Quadropods* – IMAU have been successful using broad base (4 m) 4-leg platforms, with the aim that the AWS instruments remain parallel with the slope, for example on valley glaciers with up to 9 m of annual ablation, it is advantageous to have instruments parallel to the sloping surface rather than horizontally level, to obtain data to drive one dimensional energy transfer models with coordinate system oriented along the slope. In this sense, also the wind speed appears to be to be parallel to the surface. It was not really the aim to keep the AWS parallel to the slope, but IMAU colleagues found that this is the most stable construction to operate in rough terrain (such as the margin of the Greenland ice sheet) and/or in high ablation areas. As such this design does not differ fundamentally from a tripod, it just reduces even further the risk of tipping over.

In any platform configuration, if tilting is possible, logging data from tilt sensors have eliminated uncertainties of tower level.

*Guyed pole masts* - For low accumulation zone sites with less than 2m annual snow accumulation, a very simple and inexpensive guyed pole is suitable. Guys reduce wind induced vibration and maintain the mast vertical. The settling of snow will increase the tension in the guy lines very significantly, so 5 mm wire rope and equivalent mountings are needed to prevent mechanical failure. The footprint spacing of the cables must be equitable to avoid unbalanced tension causing tower leaning.

Note that problems with snow settling can be avoided by attaching the guying cables to the end of the legs instead of using anchors. This makes the structure stiff both in accumulation episodes as well as during strong ablation. Usually it is then also necessary to connect all four legs about halfway with a single cable to avoid bending the legs upward if the guying cables are tightened.

## 4.2 Power Systems

In polar latitudes, the restrictions of power availability is a major obstacle in achieving high quality data. Further, power systems in cold climates have a number of non-obvious aspects that have been re-discovered time and again by glaciologists and meteorologists. We include some of these discoveries below.

### 4.2.1 Very low power: battery only

Most traditional AWS or similar remote systems with low power (< 1W) use a battery and solar panel. The battery needs to store power for dark periods, the solar panel to re-charge the battery and run the system during light periods. However, for polar use, where darkness may last months, the battery capacity needs to be relatively very large, unless AWS power requirements can be minimized within power storage requirements. Further, if battery capacity is required for 6 months, then doubling this capacity may be a simpler option than adding a solar panel and regulator, which can fail and drain the batteries. IMAU has operated all its AWS with lithium batteries. They have the advantage that they have good temperature characteristics and may last for many years. The obvious disadvantage is that they are relatively expensive, that transport regulations for these batteries are strict and they are not rechargeable.

### 4.2.2 Solar power + battery

For non-polar regions, AWS operated over moderate temperature glaciers (> -10°C) can use off the shelf panels and regulators. For polar regions of moderate temperature, the panel allows "intelligent operation", where active instruments (e.g. Sodars) are operated or faster logging achieved, during all but the winter months.
Panels will yield up to double the expected power output when operating over snow, due to the additional reflected power from the high albedo surface. In addition, panels work better at colder temperatures.

For polar operation, the solar panel is recommended to be mounted vertically and pointing in the direction of the equator. The power is most needed on the day the sun returns following winter, and it will appear just above the horizon. Each day following, the panel will be reducing battery drain, and finally start charging the system. Usually, the system is near fully powered by start of summer. i.e., do not put a tilt on the panel. The vertical mounting is also more robust (in general) and is best for shedding of ice/snow.

The battery / panel unit will require regulation, to prevent over charging. Most batteries take a maximum charge current that is a function of temperature, and for a given power (from panel or other source) there is a trade between just heating the battery and actually charging the battery. Get this wrong, and your system will fail in spring through overcharging the batteries when they are cold.

## *4.3 Logger housing, Mountings and Wiring*

### *4.3.1 Blizzard Static*

When dry particles of snow impact a target, the target may acquire an electrostatic charge. Wet snow does not appear to generate "blizz static", and the worst affected locations appear to be in strong katabatic zones.

Blizzard static affects electronics in two ways, destruction and interference. Destruction occurs quite simply when one part of a system charges up differentially from a second. If the two parts are electrically isolated but in proximity (< 10 cm, possibly more) the charge can equalize by arcing. Often this sparking is from a mast structure (exposed to the blizzard) to the isolated electronics. The solution is to ensure that every part of the system is electrically common, such that as the metal structure charges, so does the electrical system. This is most easily achieved by designating the zero volts point (often the "negative" of the battery) as an "earth". It is not a true earth, the whole system may be charged to a few thousand volts absolute (with small amperage). But if everything is bonded to "earth" the system will work and no sparking will occur. The above considerations will not protect the system from lightning!

A related effect is blizzard induced electrical noise, occurring when the outside plastic shielding of a signal cable acquires a surface charge, which arcs through to the cable shielding. Without shielding, the spark will can burn out the sensor or logger input channel. With insufficient shielding, these sparks generate a small current pulse in the shield. With thousands of such sparks occurring every second, the result is noise on the signal cable similar to radio frequency interference. The solution is to use complete shielding (foil) and twisted pair signal cable with differential inputs. This design should also be used for digital signals: hence use RS422 or RS485 where possible, not single line RS232. Most manufacturers will supply the alternative version.

The worst level above the snow for picking up blizzard static is below 10 cm in the saltation zone. A cable hanging in the saltation zone will be much more prone to noise than at 1m above the surface.

Care must be taken when a complex system is deployed or a system is upgraded, such as adding telemetry. Either the separate systems must be earth grounded, or communications must be ‘optical’ with a long optic cable. Again, independent circuit grounds are best shared than isolated. In the absence of a true ground, invariably the case when deploying over snow, the "earth" is taken as the zero volts level and referenced to the battery pack.

### *4.3.2 UV damage*

Sunlight degrades most plastics, and this is especially true over snow with the added insolation from the very high UV albedo surface. The use of some plastic in the AWS is inevitable, either due to the instruments purchased, the cable used, or the choice of tie-wraps (cable ties). Be prepared to replace some plastic parts each year, and test tie wraps each year for brittleness.

*4.3.3 Snow compaction*

Densification is the process by which the snow compacts under its own weight. Guy lines will tend to be carried along with the compaction. Guy lines therefore need to be over engineered, and 5 mm wire rope or better is needed, with corresponding strong rigging. One benefit of the strength of the firn is that anchors can be surprisingly small. A 10 cm square steel plate (0.01 $m^2$ area) has been found to take > 5 tons tension when buried at 1 m depth. Snow anchors made of blocks of wood are cheap, light and they work! Guy attachment points at the mast or the anchor will be the weakest point of a guy, especially if bent steel hooks or small shackles are used: these are often supplied with the mast kit and should be replaced. Exchange for chain (round the anchor) or welded eyes on the mast. If the mast is tubular, go for KeyKlamp-type fittings that encircle the whole mast.

*4.3.4 Temperature effects on equipment and people*

The air temperatures over snow often vary over a wide range, and this may be exacerbated by radiative cooling of the equipment on clear nights. This temperature cycling can loosen screw threads, bolts and nuts. "Nyloc" nuts, with an internal plastic shim work well down to -20 C, but these can be replaced with a pair of normal nuts and lock washers.

One obvious effect of temperature is that the user will be wearing gloves, or will have cold fingers. Either way, working with the AWS will be clumsy. Think about how this can be assisted by using large handles, minimal nuts and washers, simple connectors. Clumsiness also damages equipment. Use over-engineered connectors, such as the "Amphenol" or "Mil. Spec" range. When talking to the logger for a data down-load or calibration, can the user and Laptop (or equivalent) sit in a tent some distance away?

Mast mounts are often supplied as plates with U-bolts. Booms and even instruments can be mounted with scaffold clamps such as Nu-Rail or KeyKlamp. A single (studloc'd) grub screw tightens the clamp using a hex key, all possible using even the thickest gloves. Nu-rail Connectors are favored over KeyKlamp because they fix to the tower with twice the mounting, are lighter, and do not rust.

## 5. Maintenance

### *5.1 Calibration*

The importance of relative and absolute calibration of instruments cannot be overstated, especially when dealing with more than one instrument or AWS. The following considerations related to instrument calibration should be considered.

- If temperature, humidity, and wind speed measurements are made at more than one level, both the uncertainty of vertical profiles may be assessed and potentially reduced through calibration correction schemes by collecting data from the multiple instruments at the same level over as wide a range as possible in environmental conditions. For practical purposes, commonly at least half a diurnal cycle provides a useful data set for relative accuracy assessment between instruments. Such calibrations are recommended at the installation time, during site visits, and just before the station is removed. Stay on top of these and follow up thoroughly in post processing.

- As, relative accuracy may also be expected to drift over time, periodic relative and/or absolute calibration experiments should be planned. The calibration exercise provides a means to demonstrate measurement uncertainty (observational error) and in favorable cases, to boost the confidence one has in the data collected.
- Most instruments are obtained from manufacturers with some specified absolute accuracy, which may change over time and may be assessed by comparison with other instruments with known absolute accuracy. Therefore, it can be valuable to bring an instrument along, to each site, to compare with all instruments, and thus develop an inter-calibration of sites. If this is a very accurate instrument, inter-site absolute calibration may be considered.
- Humidity capacitance chips degrade with exposure to extremely low temperatures and therefore require regular calibration. One should also refer to the correction scheme of Anderson (1994) to understand one method of auto calibration of humidity instruments at low temperatures at the upper limit of their sensitivity.

### *5.2 Microclimate Drift*

Moving AWS confronts one with a troubling issue: is the AWS constantly moving through different microclimates? The extent to which this is important depends on the complexity of the topography and local shading. The example of experience in Greenland, where flow rates exceed 100 m per year, has shown that it became necessary to move the AWS to avoid it flowing into a crevasse region. At the new site, there was evidently a different microclimate, as prevailing wind direction had shifted. Pressure also would drift if the glacier is steep and fast. The extent to which microclimate drift is important is unclear, however, is something to be aware of and to include in site selection.

### *5.3 Clock Drift*

Clock drift causes an erroneous time stamp and can lead to transmitter synchronization loss. The extent of clock drift has been identified in a variety of ways, i.e., using theoretical solar radiation calculations (though be careful not to mix up with leveling errors) and nearby station pressure records. Telemetered data may include an independent time stamp with which can be compared with the station clock data. The clock drift problem has been solved with integrated GPS circuitry.

## 6. Metadata

### 6.1 Introduction

Metadata (data about data) are increasingly recognized as important for AWS programs. Table 1 lists commonly desired information concerning AWS data. We recommend these data be entered into digital files to accompany disseminated data.

**Table 1.** List of recommended metadata for AWS data

1. Position, i.e. latitude, longitude, elevation, and date when sampled.
2. Instrument types and manufacturers and serial numbers.
3. Sampling rate
4. Data logger type and serial number
5. Date
   a. Installation
   b. Visit times
   c. Calibrations to which instruments and calibration remarks including weather conditions.
6. What method used to determine true north, if made by compass, what magnetic declination was used?
7. Persons present at installation and in each subsequent visit.
8. UTC time coordinates used? (UTC should always be used)
9. What other site survey information exists, e.g.:
   a. What direction does site slope?
   b. Is surface homogeneous?
   c. What is the fetch distance to any major wind obstructions?
10. Condition of instruments and cables.
11. Details on radiation shield for temperature sensors, including ventilation remarks and if shield damaged yellowed.
12. Instrument azimuths
13. Instrument height and date when measured
14. What problems encountered on revisit.
15. What problems anticipated for subsequent visits.
16. How much is rime frost a problem?
17. Note if and how much clock drift.
18. Any other site or tower-specific idiosyncrasies should be noted.
19. Photos are recommended from different directions and catalogued for each site visit and should accompany data in dissemination.

### *6.2 Geographic Coordinates*

Precise and accurate AWS positions, including elevation to within a few m at least, are needed for the following reasons and are typically obtained only reliably using differential GPS.

- Atmospheric model pressure and temperature validation exercises commonly require height adjustments to eliminate height offset errors owing to model topography biases. Therefore, the position, particularly elevation must be known to within a few meters absolute.
- The position of AWSs on glaciers changes with glacier velocity. The year to year and multi year site displacement may be so large, that the station position needs to be logged regularly. For example, accurate AWS positions are vital to locate an AWS for remote sensing applications, for aircraft over flights, for future planning in the case that the site may flow into a hazardous part of the glacier, and for the obvious yet not always trivial site search for maintenance.

### *6.3 Miscellaneous Considerations*

- *Sensor cable length* - excessive cable lengths need to be coiled somewhere. Usually, there is insufficient space inside the data logger enclosure. Therefore, this coil would remain outside, where it is exposed to the degrading effects of UV radiation and acts as a rime frost collector. Cable length should therefore be optimized for the application but beware that spare cable length is valuable if instrument distance to logger would someday change. Note also that cable length may affect instrument response/calibration.
- *Radiometer domes* – There are shortwave and longwave radiometers available with horizontally shaped detectors, i.e. no domes. These do not collect as much rime. However, this instrument type may also be of lesser accuracy. Therefore, a decision must be made here.
- *Meltwater flow down cables* – a spurious meltwater percolation signal may occur if liquid water (from rain or melt) percolates down the temperature string bundle. A dip in the buried cable avoids this problem.
- *Guy wires* – Guy wires are attractive to use to stabilize and level the AWS. Steel 'wire rope' is the common material with diameters ranging from 2-5 mm. Experience has proven that often, the guy wires can cause more problems than they solve. In regions of net snow accumulation, guy wires become increasingly tight because the AWS tower tends to be set at a greater depth than the guy wires. Since snow compacts most near the surface, there is a net tightening effect. The force can become so great as to cause tower level-drift and eventually failure of one or more of the wires causing a more severe leveling problem. Broken or melted out guy wires can interfere with measurements, e.g. propeller-vane anemometer, acoustic surface height sensors, radiometers, etc.. Perhaps if a strain relief mechanism such as a spring is installed, guy wire troubles could be mitigated.

## 7. Quality Control Software

Quality Control (QC) and associated software indicates to the end user some criterion for confidence in the data generated by the instruments and logger system. Once the data are 'in hand', post hoc analysis can then filter out obvious errors and malfunction. This is the common understanding of quality control, but we wish to stress that QC software should be developed in conjunction with the system built, to allow greatest confidence in data which passes the QC criteria, with minimal rejection of actually good data.

### *7.1 System design and Instrument Choice: Help your QC software.*

What makes any measurement more trustworthy? One obvious way is to take multiple measurements, either repeatedly with the same instrument or preferably with two separate sensors. Taking this to its logical conclusion, with AWS being relatively cheap, and logistics relatively expensive, deploy two completely separate AWS.

Notwithstanding, once the decision has been made to only put out one system, a number of design criteria should be held in mind. Choose non-analogue instruments that either work or they don't. Compare the cup anemometer, which gradually under-reads with increased rime accumulation to the sonic anemometer, which in general works well and then fails abruptly.

Record not just mean but sigma (standard deviation) of a set of readings. Sudden high sigma for a 10 second mean of say temperature, indicates the likelihood of radio or static noise.

Know what causes reading error and know its climatology: icing is a gradual phenomenon, although "unsticking" tends to be sudden. Blizzard static occurs in high winds, and affects low signal instruments (e.g. pyranometers) more than low resistance ones (e.g. PRTs). Clocks drift at very low temperatures. Measure the causes if possible, or design methods for detecting it.

Given the well designed system, the QC software will have something to get to grips with.

### *7.2 Supervised QC*

Whilst the system is running, both in pre-deployment trials and during operation, the most vital level of QC is the (skilled) human operator, coupled to good visualization software (ViS). Lessons learnt at this stage will add to previous experience gained. The emphasis however is on suitable visualization of the data. As discussed above, data logging and the ViS data presentation should be kept separate, with data being sent to a file, which can then be read back (as read only) by the ViS. The ViS should have a number of easy to access screens which show time series and statistical output, the main purpose to detect anomalies in the data set. This is especially important during the supervised operational stage in order to identify the effect known factors (such as riming) on the measurements. The ViS should be the on-hand microscope to view what the system is recording. Useful ViS displays are

- Time series of any channel, with zoom and pan.
- Histograms
- Wind rose with variable number of arms and ability to ignore calms.
- Running mean time series with 3rd standard deviation limits overlaid.
- Channel by Channel scatter plots (e.g. RH against T).

Labview is ideal for writing ViS software, for whatever AWS system, and makes user selected channel display easy to implement. With a little work and a Nat Inst A/D/ card, it can also turn the laptop into a simple digital storage scope for those difficult in-field fault tracing.

Once the QC criteria are agreed, following experience gleaned at testing and known limits to the measurements, these can be combined into a confidence estimate for less knowledgeable users. Whatever the QC chosen, however, the AWS system should still record every record. This should be stressed: it is not the logger that manages QC, and rejects data. It is the post processing software. Invariably some aspect of the QC criteria will be wrong; everyone makes mistakes. If the logger has rejected data on the basis of erroneous QC, those data are lost forever. Hence, we may make the general comment that the non-knowledgeable, who requires all the data they get to be trusted, should never have access to the logger data, but it must pass through some level of QC software filtering before dissemination.

## 7.3 Generic QC Criteria

Each individual AWS will have its own idiosyncrasies, some of which will be captured by during testing, other will appear after (or during) the field phase. Some general criteria exist which will help to generate a robust automatic QC filter for hands-off generation of data for the non-knowledgeable user. Always be aware that the strange, peculiar and dramatic real events will most likely be filtered by such procedures: use the QC software to filter for other users, but also to bring the unusual your own attention.

### 7.3.1 Limits

Typical temperatures, wind speeds, radiation levels and so forth should be known for the area. Flag data well beyond these limits. Well beyond meaning "impossible to occur", not "unlikely to occur". Erroneous data may be binned into:

- < 5 % Error. Generally impossible to capture but does not matter anyway*.
- 5% > 100%. Serious error and difficult to capture.
- > 100% error. Obvious to capture.

* with the caveat of, say, air temperature difference, where small errors are significant. But then no one said it would be easy. For instance, in polar region, limit air temperature to –100°C up to + 20ºC. Limits get rid of gross instrument failures, but are poor indicators of riming or blizzard noise effects.

Remember to look at the difference between successive time stamps: these should be constant and known.

### 7.3.2 Statistical Filtering

Over the course of a certain time period, statistical values of the readings can be made. Variance (or standard deviation) is the most useful, to test whether a signal is noisy. Ensure that what may be noise is not actually wave effects (pressure, winds and temperature) or shadow passing (radiometrics). Statistical filtering also identifies errors of stationarity, where a reading is unusually constant. Iced up wind vanes, or open circuit channels often exhibit zero variance. Statistical filtering can eliminate some of the middle error (5% - 100%) records.

### 7.3.3 Consistency

The most fail safe method for detecting middle range measurement error is inter-comparison/consistency. Inter-comparison is simply the method of comparing two separate sensors which should measure the same thing. Consistency is deriving a compound measurement via two different data sets, e.g. measuring outgoing longwave radiation by radiometer and by snow surface temperature, or wind speed by propeller vane and by sonic anemometer. Non-agreement will highlight error, but agreement does not necessarily imply reliable data. Judicious use of comparison data, however, may allow the detection of known effects, that is, choosing two instrument sets where the resulting error will be expected to diverge.

### *7.4 Quality Control Identifier (QCI) Data*

Along with the development of GC-Net QC software, a code to track data modification was developed. Therefore, a QCI data set can accompany the post-QC data. In the GC-Net case, the QCI data set has one or more columns of QCI values for each data point. For example, non synthetic data may be given a QCI value of 1, interpolated values a QCI value of 2, air temperature data thought to contain significant solar radiation overheating error a QCI value of 3, and so on, depending on the variable. Then in the data application or reduction phase, the QCI values may be parsed depending on the data quality requirements of the given data application. For example, for computing annual means, some interpolated values can be used with reasonable confidence, whereas for input into aerodynamic profile calculations, synthetic values can give crazy results. Therefore, QCI data can be an important by-product of the raw data and can give data users more insight into possible data limitations.


## Acknowledgements

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## 8. Glossary

AWS: Automatic Weather Station
BAS: British Antarctic Survey
GC-Net: Greenland Climate Network
GLACIOCLIM: C. Vincent and P. Wagnon, Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Grenoble, France.
IMAU Institute for Marine and Atmospheric physics Utrecht, Netherlands
LMP Low Power Magnetometer: single battery, non-solar unit designed to last one year (or more) of operation with polar winter operation.
upAWS micropower AWS: single battery, non-solar unit designed to last one year (or more) of operation with polar winter operation.

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# ABSTRACTS

**Photo:** The IMAU AWS on the Morteratsch glacier. (Photo: Carleen Tijm-Reijmer)

**Photo:** The sonic altimeter on the Morteratsch glacier. (Photo: Carleen Tijm-Reijmer)

# GLACIER MARGIN MICRO-METEOROLOGY AND ITS IMPORTANCE FOR WEATHER STATION PLACEMENT

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The micro-meteorology of the atmosphere above glaciers is characterized by large fluctuations of temperature, relative humidity, wind speed, and wind direction over short distances. This becomes important when selecting the location for large, robust weather stations, which ideally would be situated where their measurements represent a large area of a glacier's surface or the area of most importance to mass balance calculations. Identifying and characterizing these areas would help guide the interpolation of data from one region of the glacier to another and from one glacier to a different glacier in a similar climatic setting.

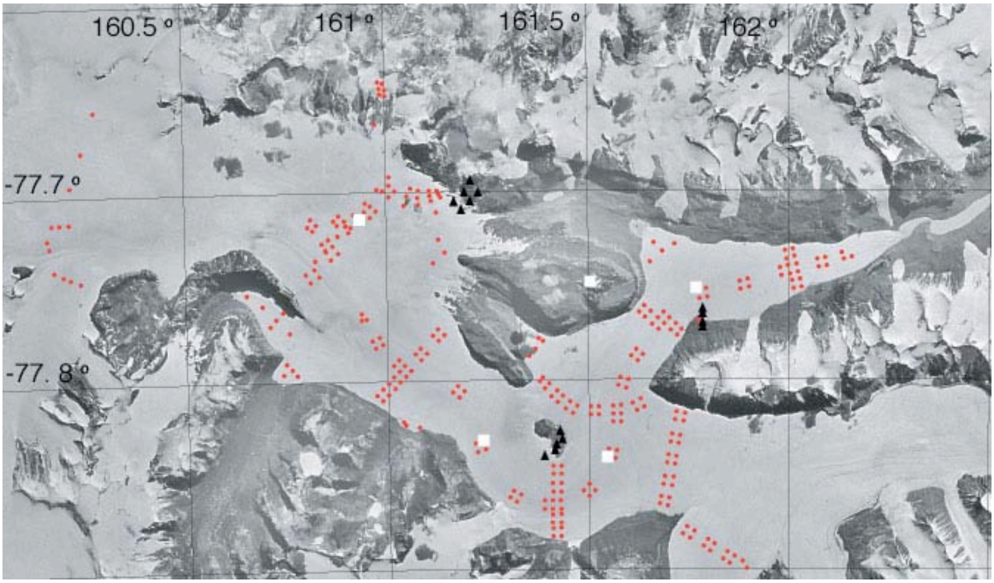


**Figure 1:** Location map of stations on the Taylor Glacier, Antarctica. Red circles are movement and ablation survey poles. Black triangles show the location of temporary weather stations we set up in the austral summer 2002-3. White squares show the location of permanent weather stations we set up in the austral summer of 2003-4.

The ablation of ice is often concentrated near the margins of glaciers, where the weather conditions can be significantly different from those in the center of the glacier, where weather stations are often placed. To understand more about the micro-climate on the margins of a glacier my colleagues from UC Berkeley and I set up six low cost weather stations (around US$300) made by Davis Inotek

Instruments on the Taylor Glacier, Antarctica in the austral summer of 2002-3. We moved the set to three different locations along the margin of the glacier (see figure 1). The stations measured temperature, relative humidity, barometric pressure, wind speed, and wind direction. In the austral summer of 2003-4 we set up five permanent, more robust weather stations manufactured by Campbell Scientific. In addition to the above parameters, they are measuring solar and longwave radiation. We ran two Davis stations in parallel with the Campbell stations for part of the '03-'04 season so we could see how well they compared.

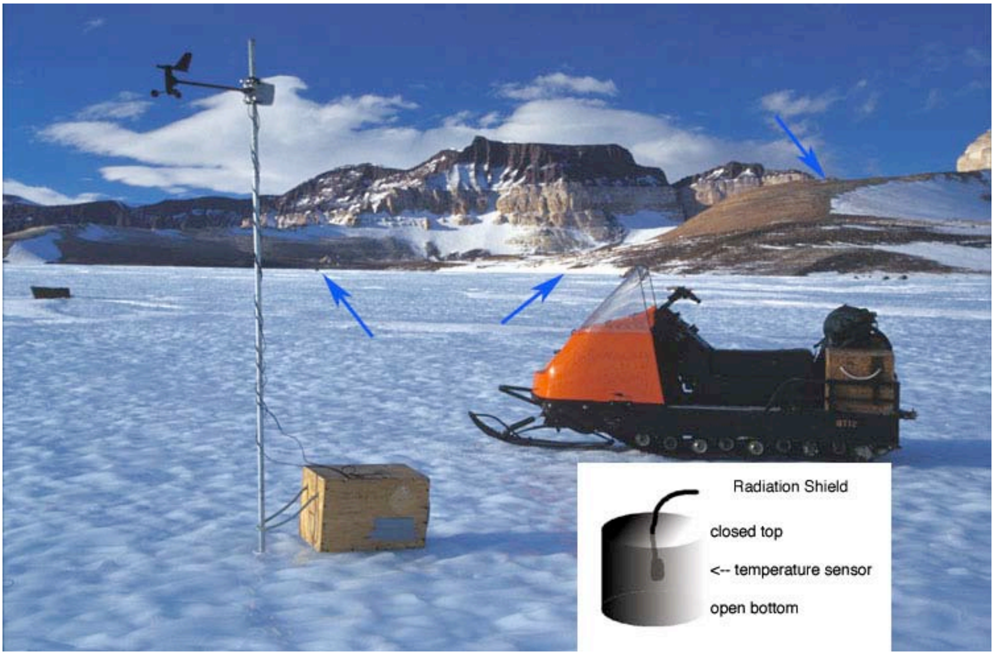


**Figure 2:** This picture shows one of the Davis weather stations in January 2003. The locations of three other stations are indicated by the arrows. The inset shows the design of the radiation shield used for the Davis temperature sensors.

The Davis temperature probes did not have radiation shields, so the measurements were plagued by direct solar heating of the sensor. To try to reduce this effect, we constructed makeshift radiation shields (see inset to figure 2) out of materials on hand in the field, primarily cardboard and duct tape. These simple cup shields worked well when the wind was blowing, but during periods of calm wind the air in the cup heated up to the point where the measurements again became unrealistic. Even with moderate to strong winds at our third location, we found that the air 2 meters above the rock surface about 1 km from the glacier margin was often 1-2 degrees colder than the glacier margin. The glacier margin, in turn, was about 1-2 degrees colder than a point on the glacier approximately 1 km from the glacier margin. This seems backwards (one would expect the glacier to be colder), but I believe the reflected solar radiation from the high-albedo glacier meant that the simple cup was insufficient for blocking direct solar heating. Commercially-designed radiation shields, while they certainly are better than mine, are not designed with high-albedo surfaces in mind so they may experience a similar, though less-pronounced, direct heating effect from the reflected solar radiation. Since this effect simply adds a fraction of a degree to the normal diurnal temperature range, it would be hard to detect and correct for. When calculating ablation of ice from weather station data, these subtle temperature errors (problems with instrumentation) and differences (real temperature variations on a small scale across the glacier margin) are amplified due to the saturation vapor pressure's exponential dependence on temperature. Of course this effect is more important in polar regions where sublimation of ice can be the dominant mode of mass loss from glaciers.

The Davis relative humidity measurements did not compare favorably with the Campbell measurements. The Davis stations never reported relative humidities much above 50% despite a number of days with calm winds, temperatures near freezing, and strong solar radiation: conditions which usually produce enough evaporation to saturate the air near the surface of the glacier. The Campbell stations did report humidities in excess of 90% on these days.

The Davis wind and barometric pressure measurements compared well with the higher-standard Campbell equipment, though the resolutions on the Davis instruments were lower.

Importance for Satellite applications: Especially for polar glaciers, where the flux of ice per glacier tends to be smaller than for temperate glaciers, mass loss due to ablation at the margins of glaciers is disproportionately large compared to the area. Hence, it would be wise to have weather stations to help calibrate satellite measurements of albedo, temperature, and other parameters not only along the centerlines of glaciers (where the measurements may represent a large area) but also at the margins of glaciers (where the measurements reflect the conditions in which a large portion of the mass loss is occurring). The additional knowledge gained should allow better predictions of the conditions at the important marginal areas of glaciers around the world and following that, a better understanding of the potential changes that glaciers will experience as a result of climate change.

# AN OPEN AWS PLATFORM

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Climetrics (a Barking Spider company), in a joint project with the Australian Antarctic Division, has developed a new generation of AWS in light of the lessons learnt from the Australian Antarctic Division's deployment of AWS in Eastern Antarctica over the last 20 years.

The first of the new generation AWS are due for deployment to Antarctica in November 2004. One of these AWS will be destined for Dome A and will be charged with the task of recording the lowest temperatures on the surface of the Earth.

## Open Sensor Interface

This AWS design provides a generic data collection and transmission platform as well as an open sensor interface (OSI) allowing third party development and rapid integration of new sensors.

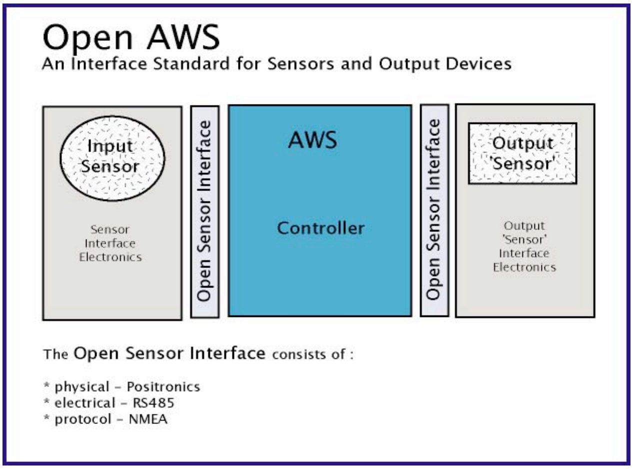


**Figure 1:** The OSI model.

The motivation for an OSI standard for AWS derives in part from a number of technical requirements, including

- the practice of running small transducer output voltages (sometimes micro-volts) over often quite lengthy cabling that is exposed to blizzard (blowing snow – static) conditions; and
- a desire to remove calibration constants from the programming of data loggers (and leave them in the hands of the people who should know best, that is the sensor manufacturers) ;

as well as a few common operational needs, such as

- sensor replacement in difficult conditions (e.g. blowing snow); and
- transfer of sensors between AWS (e.g. with different data loggers).

Sensor interface electronics have been developed to handle a range of different types of transducer outputs, such as voltage, digital data, RS232, and contact closures. These interfaces have been used with a number of common transducers such as

- Vaisala HMP45D (volts);
- Campbell Scientific SR-10 (RS232);
- Paroscientific Digiquartz (RS232);
- Middleton EP-08 (micro / milli - volts); and
- Aanderaa 3590 (Aanderaa SR-10).

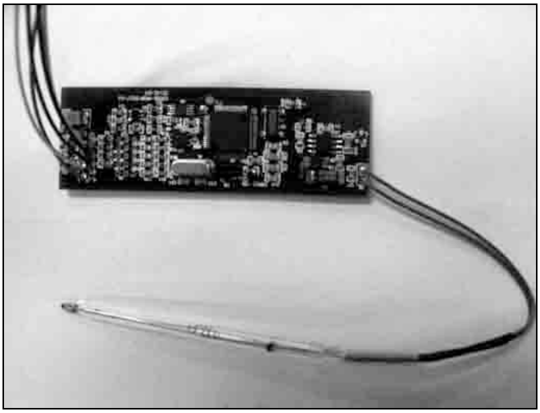

**Figure 2:** Precision temperature sensor interface and NTC thermistor. The intelligent sensor interface is used, with some transducer interface modifications, on all Climetrics' sensors.

## Intelligent Sensors

Intelligent sensor interfaces allow data reduction to occur within the sensor thus enabling more efficient use of the available satellite transmission capacity. For example, each sensor is capable of calculating minimum, maximum, average and variance for any number of samples taken at any required sampling interval.
This approach has also been applied to the output 'sensors' which have been made capable of interpreting a serial data stream and applying programmable data transformations (e.g. +100, x 50) before creating the satellite (or UHF modem, or data logger) data packet.

## Custom Sensor Designs

Custom temperature (air and sub-surface) and wind speed sensors have been developed, with the individually calibrated temperature sensors attaining an accuracy of +/- 0.02 deg. C. (for gradient studies) and the wind speed sensor remaining operational below -60 deg. C.
An un-aspirated temperature screen was developed in the '70's and has been in operation in Antarctica for over 20 years. The screen design reduces radiation errors at low wind speeds by limiting internal, reflected long and short wave radiation whilst maintaining good thermal coupling with the surrounding air.

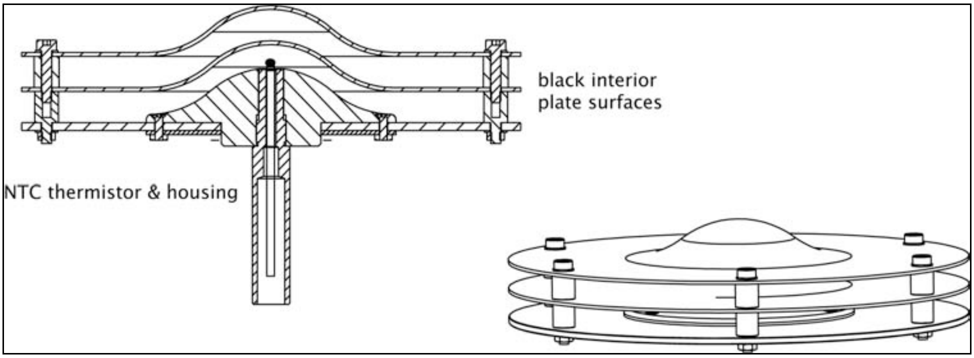


**Figure 3:** Unique temperature screen reduces radiation errors.

**Figure 4:** A Climetrics' screen beside a Young highlights the move away from an approximation to a Stephenson screen made by the three-plate design. The blackened internal plate surfaces reduce internal reflections whilst the metal plates provide improved thermal coupling.

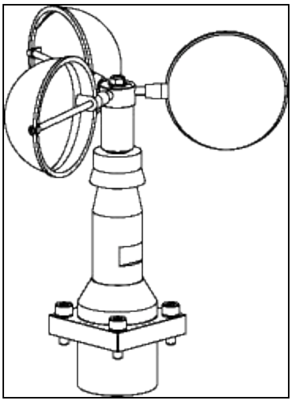

**Figure 5:** A custom anemometer design uses bearings that remain operational to -60 °C.

The problem of obtaining accurate pressure measurements in areas of high winds had been addressed in previous AWS designs by burying a vented pressure transducer in the snowpack. This solution worked well on inland deployments where there was no possibility of melt entering the vent however this was not the case on many coastal sites, where a number of venting techniques / ports were tried without success.

A pressure port was sought that might address these issues, a well tested design was settled on and a robust implementation developed for Antarctic use.

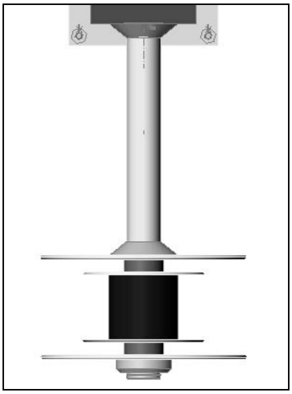

**Figure 6:** A pressure port designed to limit venturi errors. The parallel plates produce equal pressure changes in the internal cylindrical cavity. The pressure is vented to the transducer enclosure (top) from the midpoint of this cavity.

Following the repeated failure of a range of commercially available ARGOS transmitters at temperatures between –35 deg. C. and –60 deg. C. a custom designed ARGOS transmitter has been produced to allow reliable low power (no heaters) operation down to -70 deg. C.

In addition to the above features a unique folding mast design allows for deployment using small aircraft (such as an Aerospatiale AS.350B - 4-6 seat utility helicopter) in a matter of 3 to 4 hours.

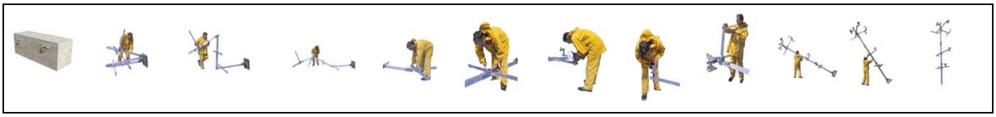

**Figure 7:** A bi-fold mast enables rapid deployment.

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A.W.S

# GREENLAND CLIMATE NETWORK: LESSONS FROM THE FIELD 1995-2003

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## Abstract

Greenland Climate Network (GC-Net) Automatic Weather Stations have been installed and visited for maintenance as part of 10 annual expeditions spanning 1994-2003, which are planned to continue for years to come. The main ingredient for successful multi-year functioning of AWS is pre-expedition planning. Still, unimagined problems arise in the field that inform future planning. This presentation surveys problems encountered in the field and ways of mitigating these problems. Problems include those associated with: power; clock drift; unwanted sensor tilt; sensor degradation; calibration; data quality control; and real time monitoring. We propose strategies to minimize data loss based on the field lessons.

# EXPERIENCES WITH THE NEW HYDRO-METEOROLOGICAL STATION “VERNAGTBACH”

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## Introduction

In the study of the climate-glacier relationship it has long been debated whether measurements taken on the glacier are to be preferred over measurements taken at stations beyond the glacier. Lang (1968) found air temperature measurements taken outside the range of Aletsch glacier, for example, to be more useful for discharge calculation purposes than on-glacier measurements using the temperature-index method. In order to ensure continuous meteorological measurements on alpine valley glaciers, great efforts must be invested in the maintenance of these monitoring stations due to the quickly changing surface properties and harsh weather conditions, whereas off-glacier stations can be operated more reliably. The contribution aims to show that the continuous operation of an off-glacier base station and short-term process-oriented studies on the glacier can complement each other in an optimal way for gaining a better understanding of the climate-glacier system.

**Figure 1:** Gauging station “Vernagtbach” at 2640 m a.s.l. with the wooden walls to protect the station from high flows, with the climate station on the right. (Photo taken 30 September 2003 by L. Braun).

## Background

The “Pegelstation Vernagtbach” hydro-meteorological station, situated at 2640 m a.s.l. in the Ötztal Alps (Austria), ~1.5 km downstream from the glacier terminus of Vernagtferner, was constructed in the fall of 1973, and hydro-meteorological data have been recorded there since then as part of a long-term glacier monitoring programme of the Bavarian Academy of Sciences (Figure 1).

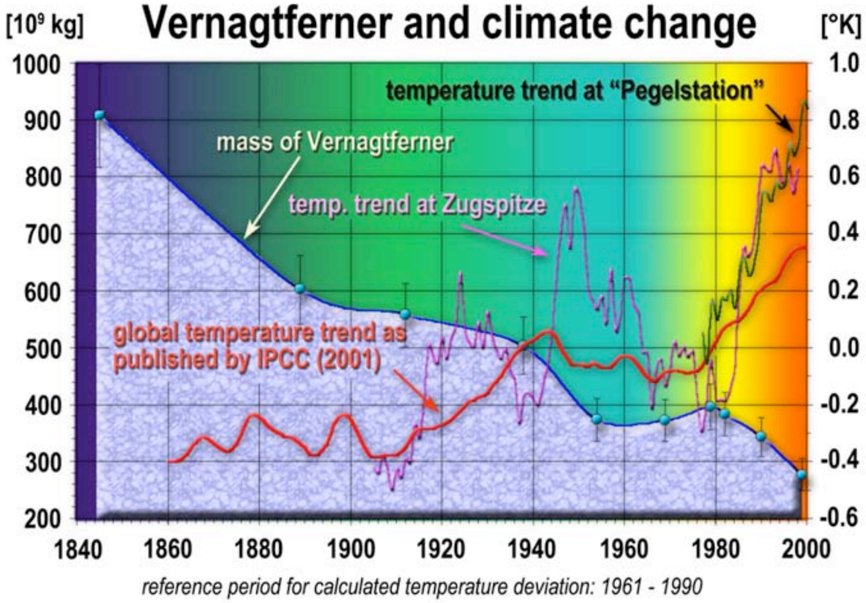


**Figure 2:** The shrinking of Vernagtferner ice mass since the middle of the 19th century and the increase in air temperature averaged over the northern hemisphere (IPCC, 2001), at the summit of Zugspitze (2962 m a.s.l.) and at the Vernagtbach gauging station (2640 m).

Direct measurements of annual glacier mass balance have been made since 1964 (Reinwarth and Escher-Vetter, 1999), and geodetic surveys of this glacier date back to 1889, when the first accurate map of an entire glacier was derived based on terrestrial photogrammetry. Based on these surveys and hydro-meteorological measurements, the reduction of glacier mass since the middle of the 19th century can be shown in a unique way (Figure 2). For comparison purposes, curves of air temperature change smoothed by a 9-year running mean are shown for the northern hemisphere, for the mountain summit station on Zugspitze (2962 m a.s.l.), and at the Vernagtbach gauging station. It can be shown that the temperature increase in the last 30 years at the Vernagtbach gauging station is nearly the same as over a span of 100 years at Zugspitze. Based on the continuous measurements of runoff, precipitation and glacier mass balance at the Vernagtferner, the individual terms of the water balance of the catchment (11.4 km$^2$, 75% glaciated in 2002) are known for positive, balanced and strongly negative mass balance years (Figure 3).

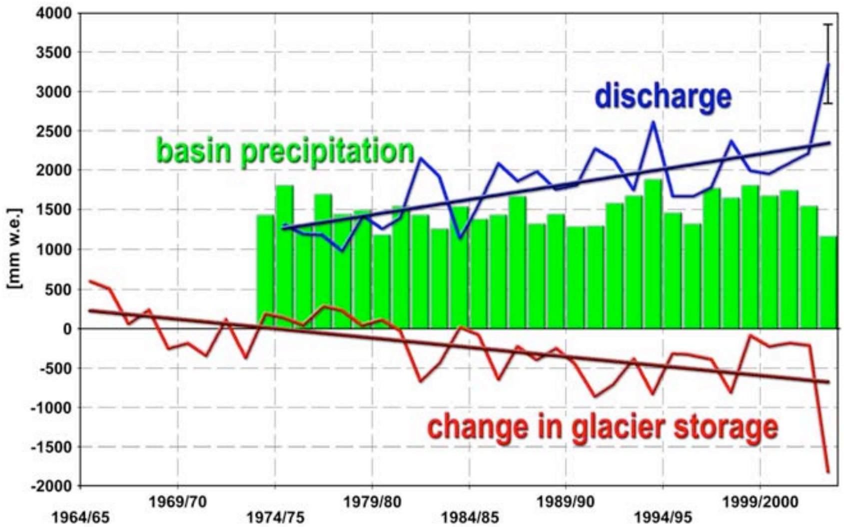


**Figure 3:** Selected terms of the water balance of the Vernagtferner drainage basin; mean evaporation (1974-1985) determined as residual is 170 mm/yr (Moser et al., 1986).

## Measurement strategy for the investigation of the climate-glacier interaction

Because of the prominent site of the Vernagtbach climate station in the valley bottom within the range of the katabatic downflow of air from the glaciated area (more than 85% of the time over a year, the wind is directed from the glacier; during melt conditions as much as 100%), the meteorological variables measured there are strongly affected by the energy exchange processes on the glacier surface. For this reason the measurements are not comparable with “regular” climate stations situated away from the mountains. For example, temperature and humidity contain less information about the free atmosphere, but more about the cooling and evaporation/condensation processes in the shallow air layer situated over the snow- and ice-covered areas. This effect depends on the distance between the station and the glacier snout, and on glacier length. Therefore, the effect diminishes with ongoing glacier retreat, which may be the reason why observed temperature changes at stations in the high mountains show a larger increase than the global mean values reported by IPCC (2001) as given in Figure 2.

To quantify the effect of meteorological variable modification at the off-glacier station in contrast to the undisturbed atmosphere, one needs to know the corresponding true values obtained by in-situ measurements directly on the glacier. Such measurements performed on Vernagtferner show a strong and general relationship between melt rates and the differences in temperature measured at both sites (Weber, 2004). This fact is in good agreement with the concept of the air temperature index method commonly used in conceptual glacier mass balance models. To determine the coefficients of such a relationship it is essential to perform sophisticated direct measurements of the components of the surface energy balance as listed in Table 1 as micrometeorological stations (Figure 4 and Figure 5). Only measurements of this kind are able to deliver melt rates at a satisfactory temporal resolution better than several hours. Once this function is known, hourly melt rates can be estimated with acceptable accuracy at simple on-glacier ablation stations (Table 1) where only (ventilated!) air temperature measurements approximately 2 m above the ice surface are needed (Figure 7). For validating the results, direct cumulative ablation measurements by sonic range sensors, ablation stakes or other methods are useful. All further required data such as tilt-sensitive global radiation or total runoff can be obtained at the off-glacier base station.

**Figure 4:** Measurement of energy balance components with the HyMEX-Station using Eddy-Correlation-method and a 9-m-profile-tower on Vernagtferner August 2000 at 2995 m a.s.l. At the left side the required mobile power station and two tents to shelter the data acquisition computers. (Panoramic Photo taken by M. Weber)

**Table 1:** Hydro-meteorological measurement scheme in the Vernagtferner basin.

| Station | Variables measured | Type of measurement | Type of information |
|---|---|---|---|
| Permanent off-glacier gauging station Vernagtbach (2640 m a.s.l.) | Discharge, air temperature, relative humidity, precipitation, wind speed and direction, short-wave rad. balance, net all-wave rad. balance, snow depth | Continuous | Continuous background information on glacier discharge and climate, influenced by the glacier's Katabatic wind zone |
| Summit station Schwarzkögele (3070 m a.s.l.) | Air temperature, relative humidity, wind speed and direction, short-wave incoming radiation; Daily photographs of the surface conditions of Vernagtferner (melting of the winter snow cover) | Continuous | Background information on climate outside the Katabatic wind layer |
| On-glacier micrometeorological experiment stations | Direct measurements of all components of the surface energy balance to obtain ablation rates at high temporal resolution | A few days during strong melt | Detailed insight into the ice melt processes, especially on the structure of turbulence and radiation balance |
| On-glacier ablation stations | Ice surface lowering (sonic range sensor) and ventilated air temperature | Continuous over ablation season | Point-information on the course of ablation and air temperature at various points on the glacier |

Parallel to the continuous hydro-meterological measurements taken at the gauging station (2640 m a.s.l.) situated some 200 m lower than the glacier tongue, an additional automatic weather station is in continuous operation on Schwarzkögele (Figure 6), an easily accessible mountain summit with an elevation of 3070 m a.s.l., which corresponds quite well with the equilibrium line altitude of Vernagtferner under balanced conditions (3080 m). From this daily photographs are taken of the glacier area to document the melt out of the glacier surface and thus the temporary snow line.

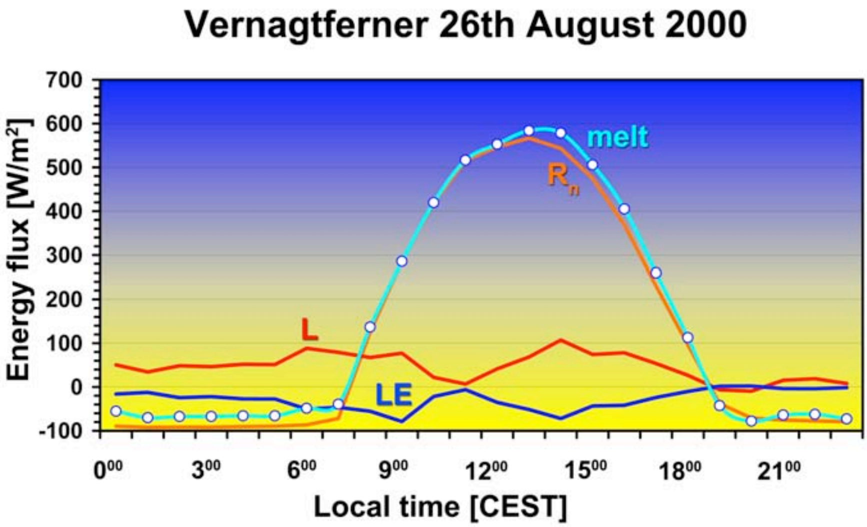


**Figure 5:** Results of hourly averages of the measured components of the surface energy balance and the available melt energy during the field experiment HyMEX 2000. (Rn: net radiation, L: sensible heat flux, LE: latent heat flux).

## Long-term operation of the off-glacier base station

Comprehensive long-term observations over decades are needed in order to detect evidence of climate change in the past and in the future. Due to the "long memory" of the processes involved, it is necessary to provide information over a period long enough to explain the current evolution of glaciers in the glacier-climate relationship. Therefore, the data series need to be continuous and homogeneous. These requirements are not easy to fulfil, even for stations off the glaciers. As can be shown using the example of the Vernagtbach gauging station major revisions were necessary in order to adapt to changes in discharge conditions, measurement techniques and available funding.

In October 1995 and July 2000 the measurement channel of the gauging station had to be rebuilt to adapt flow capacity to increased daily flood peaks (Figure 1; Reinwarth and Braun, 1998). The diurnal variations of glacier discharge had increased over the years due to strong glacier mass losses since 1980 and the thinning of the firn areas (Figure 3). These structural adaptations were absolutely essential to protect the gauging stations against flood damage, in particular when strong melt was combined with intense rainfall.

**Figure 6:** Automatic summit station “Schwarzkögele”. (Photo taken in 2000 by T. Naeser).

**Figure 7:** “On-glacier” ablation station, equipped with a sonic range sensor and a ventilated shielded Pt100-thermometer. (Photo taken in 2003 by M. Siebers).

In November 2001 the meteorological instruments and data loggers were completely replaced by a modern Campbell system and run in parallel with the former data acquisition in operation since 1984. Included among the new devices are ventilated air temperature sensors, a Belfort precipitation gauge (measurement of hourly precipitation), and a sonic range sensor of snow height. SMS messages with selected data are sent to Munich daily, which facilitate quality control and the checking of current climatological conditions at the gauging station. Furthermore the data are instantly made available via the world-wide web under the addresses www.glaciology.de and www.glaziologie.de. The power supply for the whole station is derived from solar panels, including the ventilation of sensors and the transmission of the data to Munich.

## Conclusions

The monitoring concept as realized in the Vernagtferner basin offers the unique option to conduct investigations of glacier evolution. The conventional geodetic and direct glaciological determinations of glacier mass balance can be validated additionally by the hydrological method based on the determination of the water balance components. With this scheme of investigation there is no disadvantage to installing the permanent base station off-glacier because hydro-meterological data can be obtained more reliably, accurately and completely over extended periods than is the case for on-glacier stations.

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# ANTARCTIC THE LARGEST GLACIER OF THEM ALL

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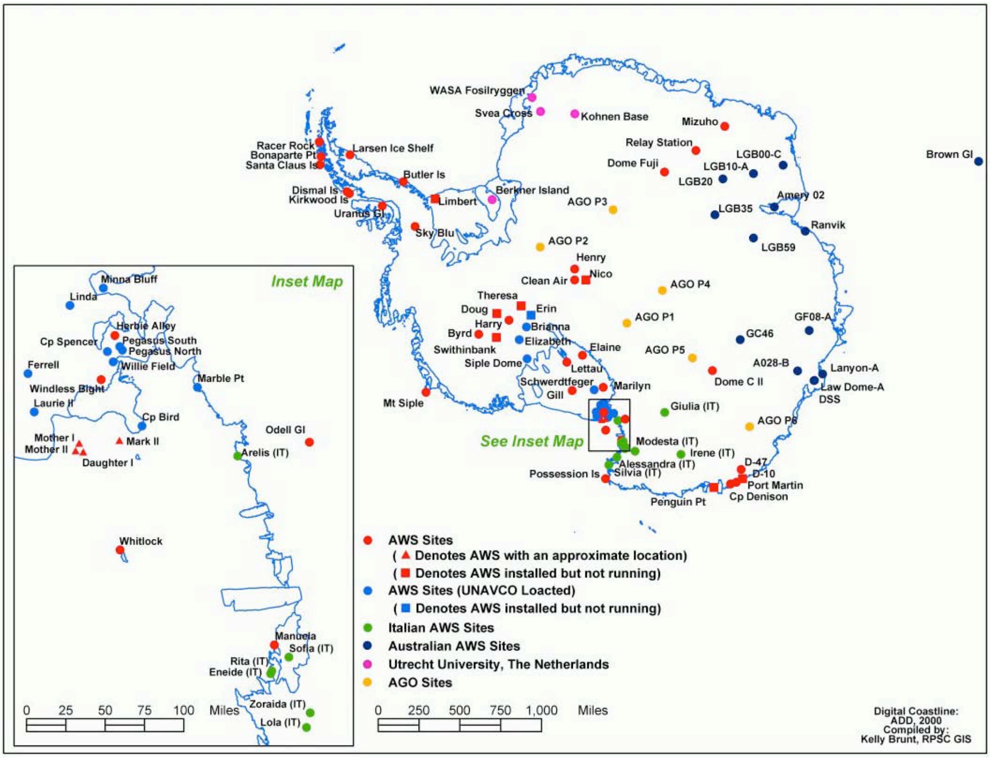
## Introduction

Antarctica is the highest, coldest, driest and windiest continent on earth. More than 99% of its surface is covered by an ice sheet up to 4700 m thick and the mean elevation is 1930m above sea level. The mean annual temperature is –37°C ranging from –2.4°C at the northern extremity of the Antarctic peninsula to –60°C on the high inland plateau of East Antarctica.

Antarctica is about 50 times the size of the UK and is a very data sparse area, most of the manned stations are around the edge of the continent and in-situ meteorological data can only be collected over most of the interior by the use of automatic weather stations (AWS).

Near real time, three-hourly synoptic data from approximately 80 AWS are distributed directly by Service Argos via the World Meteorological Organisation's Global Telecommunication System. These are maintained primarily by America, Australia and Italy. There are also many smaller units, operated by most of the international operators that log the data onboard and have to be visited every year to collect the data.



The problems associated with operating AWS in the Antarctic fall into two categories; operational and environmental.

The main operational difficulty is the fact that there are only about 4 months of the year (November – February, the Antarctic Summer) that aircraft can be flown in Antarctica due to the fact that outside of these times it is too cold and dark. Practically all of the AWS can only be visited by aircraft as they are in very remote locations and it is not possible to visit all of them every year so a priority list must be made of which to visit.

The environmental difficulties are more varied and consist of the fact that in some places there may be no sunshine for 6 months and so extra batteries have to be installed, extreme cold conditions down to –90°C, high accumulation rates mean that in some areas AWS have been completely buried and lost in only a couple of years and static electricity charge can build up on the instruments and cause the electronics to fail.

## British units

The British Antarctic Survey service five of the American AWS on the Antarctic Peninsula but it also operates 10 of its own. The units were developed at BAS and consist of a Tattletail logger and associated electronics. The units are very low power and draw on average only 1mA due to the fact that they do not transmit the data. The data are logger every hour and then stored on an onboard memory card which is then downloaded very year. The units have been designed so that all of the component parts (except the 6m pole mast) can fit inside one metal box for transportation.

## American units

The Radio Science Laboratory at Stanford University developed and deployed the first AWS units. The basic AWS units measure air temperature, wind speed and wind direction at a nominal height of three meters above the surface, and air pressure at the electronics enclosure at about 1.75 meters above the surface. The heights are nominal because of snow accumulation that may occur at the site.

The operations of the AWS unit are controlled by a small microcomputer operating at 819kH using a read-only-memory (ROM) of 2024 x 8 with 256 x 8 random access memory (RAM). The microcomputer updates the data at a nominal 10 minute interval and at 200 second intervals transmits 256 bits of data. The transmissions are in the blind and if the NOAA satellite is within line of site of the AWS unit, the transmission will be received and stored by the ARGOS DCS.

The AWS unit is powered by six to twelve 40 ampere-hour 12 volt gel-cell batteries charged by one or two 10 Watt solar panels. At the South Pole, 12 batteries and two solar panels are sufficient to operate the AWS unit through the year, while six batteries and one solar panel are adequate on the Ross Ice Shelf. Several of the AWS units have operated on the same batteries and solar panel for 6 to 10 years.

## Australian units

The AWS used are designed and built within the Australian Antarctic Division. Three different station designs have been used over the past two decades. All stations use the ARGOS data relay system, carried by the NOAA series of near-polar orbiting satellites. All stations measure air temperature, atmospheric pressure, wind speed and direction. Most measure air temperature and wind speed at more than one height, providing data on near-surface vertical gradients, a check on the data accuracy, and some instrumental redundancy. Some stations have additional sensors measuring snow temperature at different depths, atmospheric humidity, solar radiation and height of the sensors above the snow surface (which changes due to snow accumulation and ablation) as well as several "house-keeping" parameters (voltage, internal temperature, etc.)

The main station consists of a mast with instrument arms at 3 levels (nominally 1, 2 and 4 m above the surface). Shielded air temperature sensors and anemometers are mounted on these arms. Other sensors mounted on arms include humidity, wind direction and snow surface height. There is a pyranometer mounted on the very top of the mast to measure incoming solar radiation, and sub surface snow temperatures are measured with a buried thermistor chain. The AWS controller, Argos satellite transmitter, power regulation circuitry, pressure transducer and batteries are mounted in a box at the base of the mast. Batteries are recharged during summer by a small, vertically-mounted solar panel near the top of the mast. The AWS draws an average of only 3 mA of 12VDC power, with the satellite transmitter consuming approximately 95% of the total power.

The first Australian AWS were deployed during over-snow glaciological traverses. AWS were deployed in Wilkes Land in the mid 1980s during IAGP traverses International Antarctic Glaciological Project) from Casey towards Vostok, and around the 2000 m ice sheet elevation contour. In the late 1980s and early 1990s a series of AWS were deployed along the 2500-m contour around the Lambert Glacier Basin during the LARGE project (Lambert-Amery Regional Glaciology Experiment). Later stations were also deployed by aircraft and most recently a number of stations have been deployed at potential sites for an airfield for an intercontinental link between Australia and Antarctica.

# Greenland Climate Network: Future measurements

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Since its establishment in 1995 the Greenland Climate Network (GC-Net) has provided climatological and glaciological information in most climate regions of the Greenland ice sheet. Each AWS measures 32 parameters, including temperature, humidity, wind speed and wind direction at two levels, shortwave incoming and reflected radiation, net radiation, snow height, pressure, snow temperature at 10 depths, GPS time and location. The Summit AWS in this network continues observations begun in support of the GISP2 project in 1987 (Shuman et al., 2000), which has been useful to studies of snow photochemistry at this site. However, to quantify the impact of snow photochemistry upon the composition of surface snow and its overlying atmosphere standard climate observations from the existing AWS at Summit are not adequate. To help support existing GC-Net measurements an integrated field program of research at Summit, Greenland took place during the summers of 2000 and 2001.

One of the most important challenges to providing reliable diffusion coefficients for flux calculation at Summit is to demonstrate that its weak and intermittent turbulence can be adequately characterized using existing instrumentation. It has often been felt that measurements of turbulence have been hindered by lack of reliable, fast-response sensors, especially in very cold climates where conditions for such measurements are particularly difficult. In these often stable environments, a significant part of the turbulent flux is carried by small scale eddies. Because sonic anemometers have a finite instrument response time there is a concern that an inadequate sampling rate may result in a fraction of the small-scale flux being omitted from the chosen averaging period. Flux loss may also occur because an instrument may not be capable of fully capturing the turbulent fluctuations being monitored. The quantification of turbulent structures enables one to make informative decisions regarding the ability of fast response sensors to capture "energy containing" eddies. On a practical level this information can be used to determine the frequency requirements for sensors operating in this type of environment.

Using knowledge gained from the additional measurements made at Summit our research group is proposing to use the Summit AWS as an experimental site for upgraded measurements. The additional instruments that we propose to mount on the AWS tower at Summit for year round measurements include: (1) An eddy correlation system equipped with heated sensor heads on the sonic to enable measurements during winter, (2) Ventilated temperature and humidity measurements, and (3) An IR transducer for snow temperature measurements. The anticipated problems associated with obtaining useful data from these measurements in context of "lessons learned" at Summit are assessed. Information regarding necessary system upgrades on the existing AWS to conduct these additional measurements is also described.

# AUTOMATIC SNOW AND WEATHER STATIONS IN THE SWISS ALPS

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## Introduction

In the last few years automatic snow and weather stations have become an important tool for practitioners dealing with alpine hazards in the Swiss Alps. By now more than 150 of our automatic snow and wind measurement stations for avalanche warning (cf. Figure 1), 15 alarm stations for different alpine hazards and scientific stations on glaciers provide important data for warning, protection and scientific research. These stations are operated autonomously throughout the year. They run under high alpine environmental conditions with a minimum of maintenance. The understanding of the physically correct way of measuring is as important for obtaining good and reliable data as is an optimal design of the stations. This includes the data acquisition, energy supply and communication subsystems as well as the mechanical structure. Furthermore, the wide range of available sensors and the use of specifically developed measurement systems offer interesting solutions for automatic stations on glaciers.

**Figure 1:** Automatic weather station for avalanche warning in the western Swiss Alps (Simplon Wenghorn, 2420m a.s.l.)

Most of our stations are based on data loggers from Campbell Scientific (http://www.campbellsci.co.uk). With these devices, virtually every type of sensor signal can be logged with high resolution and quality. Additionally they offer a wide range of programming features and are completely controllable and programmable from a remote location.

### Measurements

The standard meteorological parameters like wind speed and direction, air temperature and humidity or atmospheric pressure are measured on most automatic stations. Parameters like snow depth, infrared surface temperature, shortwave radiation, snow and ground temperature, snow wetness and density or snowdrift characterize the properties of the snow pack. Moreover, radiation or energy flux balances, water pressure and level measurements, drilled temperature profiles, dislocation measurements, extensometers or TDRs can be logged without any problem.

### Camera system for observations on glaciers

Our autonomous camera system has been specifically developed for operation under harsh ambient conditions. Due to its high-resolution digital camera it is well suited for detailed observation of slow movements like the opening of crevasses. The images can be stored in the camera system or transmitted by a data link. The solar power supply and the rugged, double-walled metallic housing allow a maintenance-free autonomous operation even under high alpine environmental conditions. Figure 2 shows an image of the Trift glacier in the Swiss Alps taken with an automatic camera.

### Distributed measurements

The use of a simpler type of data logger with spread spectrum radios allows flexible configuration of sub-networks composed of a data concentrator and distributed sensors. Thanks to this technology it is possible to link the data from distributed measurement points without having to connect them by cable but all the same at low costs.

### Power supply and communication

In most cases our automatic weather stations have to run completely autonomously and with high reliability throughout the year. For this reason they are optimized for low power consumption and equipped with a solar power supply. Measured data can be stored in the extendable internal memory of the station and read out manually. Of course data transfer over a radio, GSM or satellite link is possible as well. Additionally complete control and programming from a remote location can be achieved using a communication link.

### Mechanical construction

For our normal stations we use a standard 6.5m steel pylon, which is mounted on three anchors. For smaller pylons up to 5m and subjected to a maximum torque of 3kNm we developed a special anchor system. This construction is particularly suitable for the use on ice- and rock-glaciers because it is very flexible yet economical. The three arms of the anchor system can be adjusted to the shape of the terrain and can either be fixed to the surface or buried into the ground. Furthermore the anchor system can be mounted on any supporting platform. Thanks to the simple installation it can easily be removed and readjusted.

## Well adapted and cost-effective solutions

The needs and circumstances for scientific measurement systems vary widely from case to case. So there is no need for standard solutions. We like to attack the challenge to find the optimal solution for your measurement problems making the most effective use of the available resources.

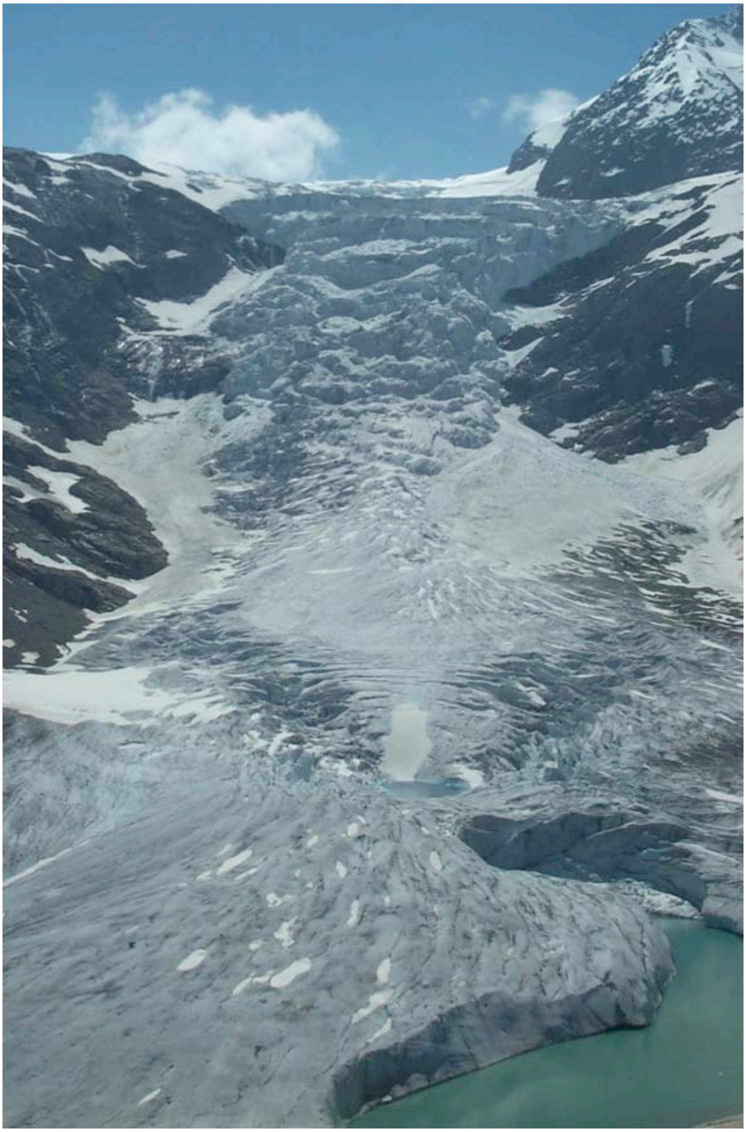

**Figure 2:** Picture of the Triftgletscher in the western Swiss Alps taken by an automatic camera system.

# HIGH-ELEVATION WEATHER STATIONS ON GLACIERS IN THE TROPICS AND THE HIGH ARCTIC

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Our climate research employing automatic weather stations (AWS) focuses on high-elevation glaciers at low latitudes, and on an ice cap at 81°N. Each AWS is designed to operate autonomously and continuously, for a multiyear period. The first of these was deployed in 1996, and two continue to operate in 2004. Design considerations, instrumentation and the performance of each station are illustrated and discussed.

Four high-elevation AWS sites coincide with locations from which ice core records were obtained. Nevado Sajama is in the Cordillera Occidental of Bolivia (Figure 1, left-hand image; 18°06'S, 68°53'W and 6542 m), where an ice core was obtained in 1997 (*1*). Our station operated for four years (*2–6*). Also in Bolivia, we deployed a station in the Cordillera Real at 16°39'S, 67°47'W at 6265 m on Nevado Illimani (*7*) near the site of 1999 ice core drilling (*8–10*). A new station is currently operating on Quelccaya Ice Cap in Perú (13o 56'S, 70o 50'W and 5670 m), where long ice cores were drilled in 1983 and again in 2003. In Africa on the Northern Icefield of Kilimanjaro (3°04'S, 37°21'E and 5794 m), an AWS has operated continuously since 2000 (*11–16*). Our high-latitude site was on the Murray Ice Cap, northern Ellesmere Island (81°21'N, 69°15'W) at an elevation of 1,100 m. Here, an additional AWS on a 10-meter tower operated seasonally through three summers (Figure 1, right-hand image). Measurements were undertaken at this site to better understand glacier-climate interactions, and areal changes in glacier extent through time (*17–19*).

**Figure 1:** AWS on Sajama (left), Quelccaya Ice Cap (center), and Murray Ice Cap (right).

Design concerns and considerations for the Sajama AWS included uncertainty about the magnitude and inter-annual variability of wet-season accumulation, high wind speed during the winter, and visitation by climbers. Of these, only the magnitude of precipitation presented a significant problem, due to sensor burial and tensioning of guy-wire cables. Additional issues included unreliable GOES telemetry and electrical activity apparently associated with blowing snow and/or convection.

The Illimani AWS design was similar to that on Sajama. Site location was compromised to prevent interference from climbers, leading to unrepresentative temperature measurement and enhanced snow accumulation. High precipitation associated with anomalously low sea surface temperatures in the equatorial Pacific Ocean created hazardous conditions for personnel in September 1999 (7), and prevented visitation of the station in October 2000 and October 2001. Sometime prior to November 2001, accumulation buried the entire AWS and the station has not been recovered. GOES telemetry was also unreliable on Illimani, and on one occasion lightening or stray electrical activity seriously damaged the electronics.

Quelccaya Ice Cap's high accumulation rate (2–5 m; L. Thompson, 2003 pers. comm.), dictated a AWS design in which all sensors were initially 4.5 m above the snow surface (Figure 1). Lightning protection was also incorporated into the design. Shortly after deployment, telemetry via an improved, High Data Rate GOES transmitter ceased. The station will be visited late in March to collect data (hopefully) and ascertain whether the transmitter failed or vandalism occurred.

The AWS design for Kilimanjaro was done without knowledge of the current horizontal surface mass balance regime. Visitation by climbers on this popular mountain was also a concern. Telemetry using Argos was added after the first year, which has performed flawlessly. Excellent overall reliability of the station is aided by low air humidity and high solar radiation (Figure 2), and we therefore hope to continue measurements for the balance of the decade, to better understand the glacier's response to inter-annual climate variability.

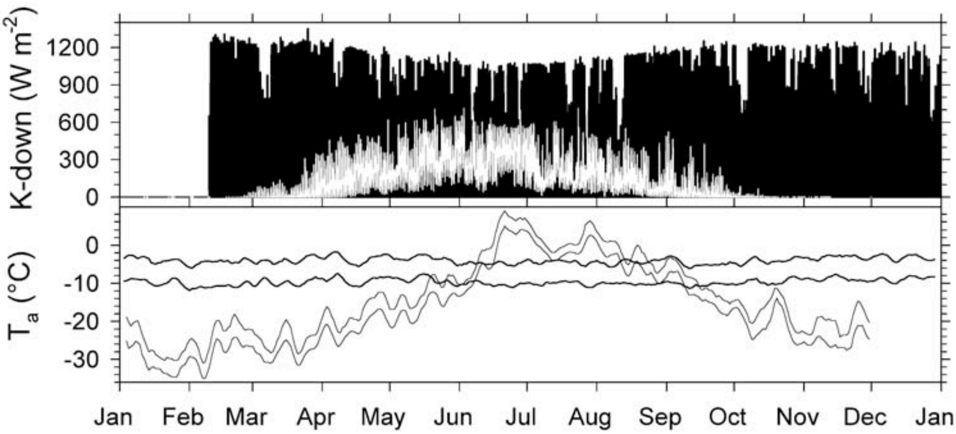


**Figure 2:** Contrasting seasonality at two AWS sites, with implications for instrumentation and power budgets. Upper panel is global solar radiation (hourly) on Kilimanjaro (black lines) and on Murray Ice Cap (white lines). Lower panel illustrates max/min daily temperatures for the same sites; Kilimanjaro is shown as the darker line.

Design considerations for the AWS on Ellesmere Island were very different from those for the low-latitude sites, due in part to the extreme difference in climate seasonality (Figure 2). At this latitude, virtually no solar radiation receipt for five months each year limits the availability of power. Riming of sensors is problematic through all seasons but winter, but was greatly reduced on radiometers by ventilation. Animal visitation presents a challenge to arctic AWSs, even on glaciers, and at this site a persistent fox eventually penetrated our defenses.

All of these AWS have some components in common, and some are unique. Our experience with the reliability of specific electronics and instruments are also discussed.

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# DIFFERENCE BETWEEN VENTILATED AND UNVENTILATED TEMPERATURE MEASUREMENTS OVER SNOW SURFACES

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## Introduction

Air temperature measurements are of major importance for many issues in glaciological research, particularly in melt and energy balance studies. Air temperature measurements are subject to errors due to radiational heating. This error commonly referred to as radiation error can be considerably reduced by artificially ventilating the temperature sensor. However, in practice, particularly in glacier research, often the temperature sensors employed, are only equipped with some type of radiation shield, but no artificial ventilation. We performed a comprehensive field experiment to systematically investigate the radiation error and its controls.

## Methods and study site

For a period of more than seven months (10 November 1995 to 24 June 1996) three ventilated and six unventilated temperature sensors were placed side by side over a snow surface at the experimental site of the Snow and Avalanche Institute (SLF), at Weissfluhjoch, Davos (2540 m a.s.l.). The ventilation was designed and constructed at ETH and measurements compared well to ventilated air temperature data collected by the Swiss reference instrument 'Thygan' operated by SLF. In addition wind speed and detailed radiation data were available during most of the experimental period from a simultaneous experiment on radiation by Ch. Marty. We compared three different types of radiation shields (Figure 1): Mierij, Aanderaa and Young and also different types of sensors (Rotronic, Campbell, Aanderaa). The site is subject to a long-lasting snow cover throughout the winter.

**Figure 1:** Radiation shields used in the experiment: Young (left), Mierij (middle), Aanderaa (right).

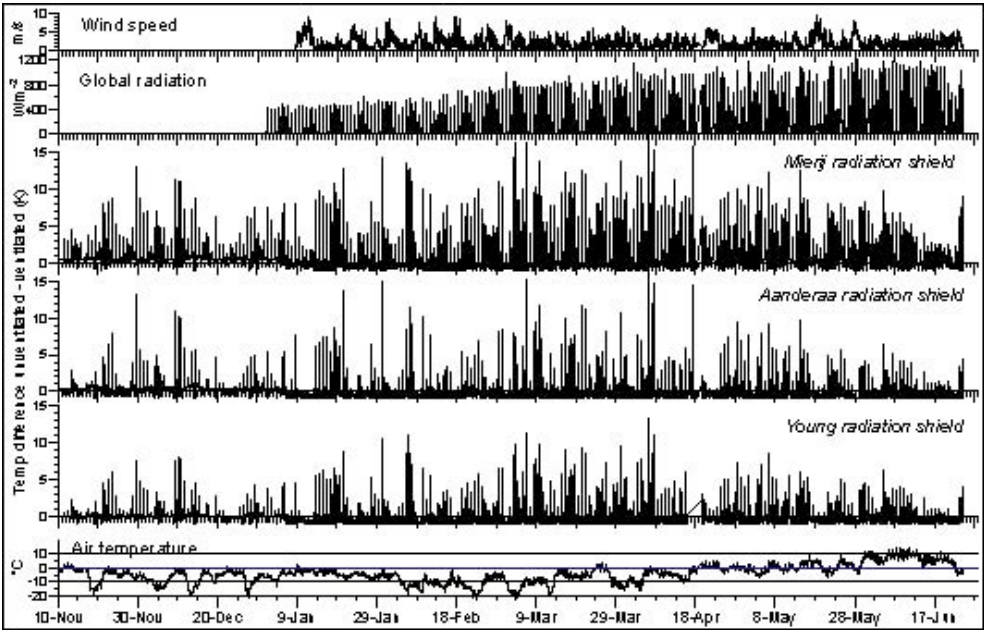


**Figure 2:** 10-minute averages of wind speed, global radiation, air temperature and the difference between unventilated and ventilated air temperature using three different types of radiation shields at Weissfluhjoch, Davos, from 10 Nov 1995 – 18 June, 1996.

## Results

Temperatures recorded by the ETH-ventilated and the unventilated sensors deviated considerably from each other, 10-minute means differing up to more than 15 K on clear-sky days (Figure 2). Deviations showed a pronounced diurnal pattern increasing strongly with increasing global radiation. High wind speeds tended to reduce the deviations. Figure 3 indicates that the Aanderaa radiation shield although smallest in size performs best, the Mierij one worst with the Young shield in between. For the Aanderaa and the Young shield a wind speed exceeding 3 and 5 m/s, respectively, are needed to restrict the error to less than 0.5 K (Figure 3). We suspect that the high albedo over snow is responsible for the large deviations observed.

Although results refer to this specific site characterized by high albedo and high elevation, it is obvious that accurate temperature measurements over snow with the commercial sensors used can only be achieved when the sensors are artificially ventilated. The commercially available radiation shields are far from sufficient to yield accurate temperature estimations under such conditions. Over snow and during clear-sky conditions, the measurement error can exceed the one given by the manufacturers by one order of magnitude.

## Acknowledgements

We gratefully acknowledge the excellent logistical support by Martin Hiller (SLF) and thank Christoph Marty for providing radiation data. Juerg Joss helped to select the measurement site.

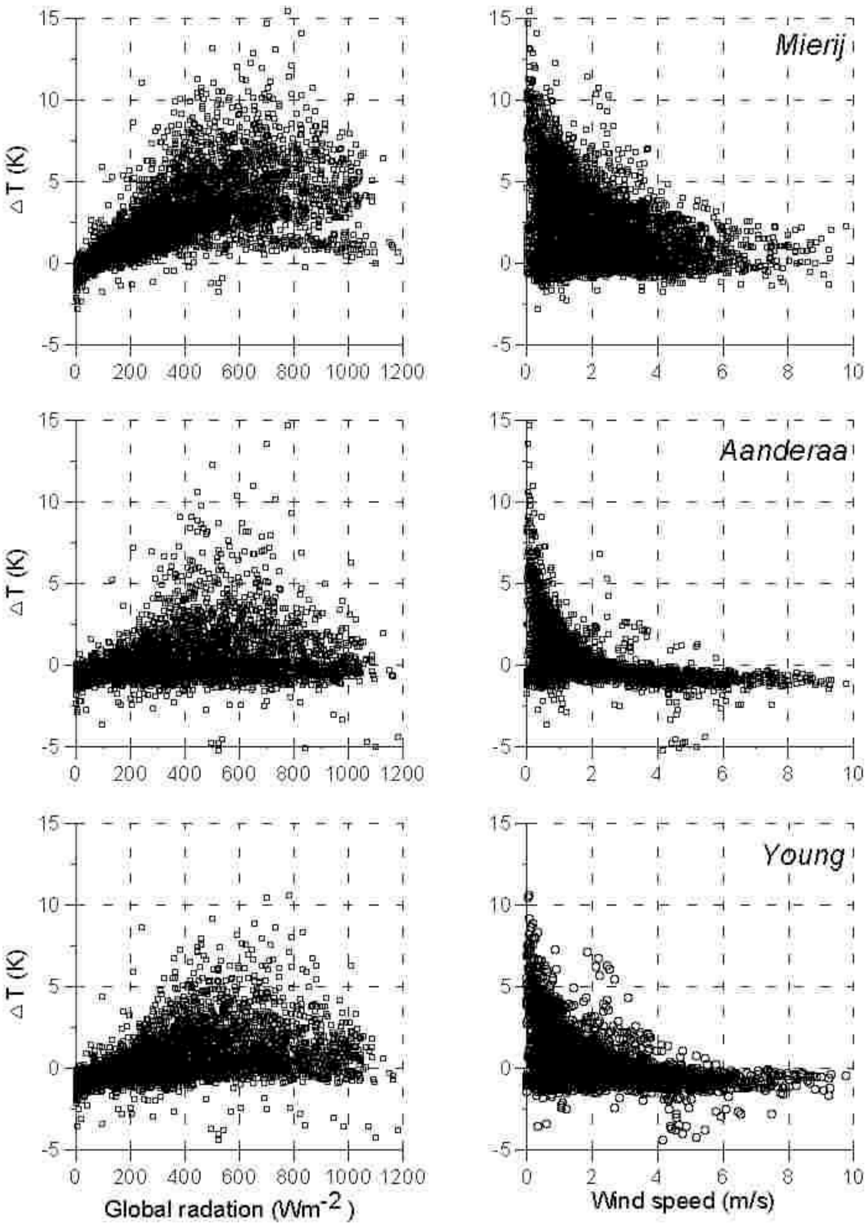


**Figure 3:** Differences between unventilated and ventilated air temperatures (10-minute averages) versus global radiation and wind speed.

# An AWS mounting device which mechanically adjusts itself to changing glacier surface conditions

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## Introduction

In principle, corrections of data series can only be an alternative option, while avoiding errors must be the primary effort. This is not possible in many cases, e.g., when measuring air temperatures above highly reflecting snow surfaces. A constant height of sensors above the glacier surface and a permanently horizontal position of instruments, however, can be achieved with an appropriate mounting device.

## Background

An ongoing research project financed by the Austrian Science Foundation FWF and carried out by the Innsbruck Tropical Glaciology Group in the Peruvian Cordillera Blanca aims, among others, at modeling glacier mass balance and melt water production for different time scales. Therefore, a model was developed which meets both the low latitude climate circumstances and the poor availability of data in low latitude countries (Kaser et al. 2003). It is thought for glacier climate studies as well as for glacio-hydrological applications (Juen et al. 2003). Tropical climate is characterized by minor seasonal temperature variations but by more or less pronounced hygric variations during a year. Consequently, ablation on glaciers occurs all year round and accumulation is tied to the hygric seasonality. In the ablation areas, weather is similar to mid-latitude summer conditions. Tropical dry periods are like clear-sky summer days with ablation being reduced by strong cooling during the night and considerable sublimation during daytime (Wagnon et al, 1999). Wet seasons are comparable to wet summer days with occasional snow fall or rain, high atmospheric long wave emissivity, little cooling during night, and highly efficient ablation due to melting. As a consequence, a thick and persistent snow layer such as during winter and spring in the mid latitudes, cannot develop. Snow cover, however, seldom lasts for more than some days. All year round ablation results in considerable mass loss and frequently varying glacier surface conditions. To reach tropical glacier sites usually takes several days from major settlements and requires animal and man power for transportation. For these reasons, during our research project, sites are visited two times per year only. Among others, the model calibration and validation requests for information about long and short wave radiation fluxes to be obtained from a glacier automatic weather station (AWS). Due to this circumstances, a mounting device was designed and constructed which maintains (i) a constant height of sensors above the ablating glacier surface and (ii) a horizontal position of the sensors mounted, no matter how the glacier surface changes.

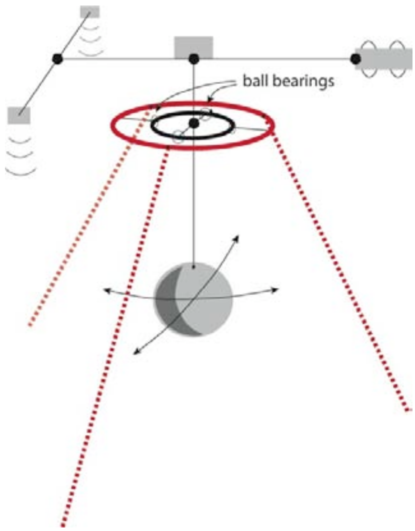


**Figure 1:** The design of the self-adjusting AWS mounting device.

## The design of the mounting device

The core of the mounting device is a pendulum, which hangs in a inner metal ring on two slewing ball bearings. This enables swinging along one axis. The inner ring is connected to an outer one in the way that swinging in an axis normal to the first one is ensured. The outer ring is fixed to a tripod, which freely stands on glacier ice. The pendulum has a weight on its longer, downward-directed arm whereas the jibs on which the sensors are to be mounted, sit on top of the short upward part. A clino-meter on top of the mobile portion of the device provides constant information on how reliably the horizontal position is maintained. Spires on the tripod shall prevent the device from sliding on bare glacier ice. Figure 2 shows the cardan-like joint in a close up during the first mounting of the mast at our Institute.

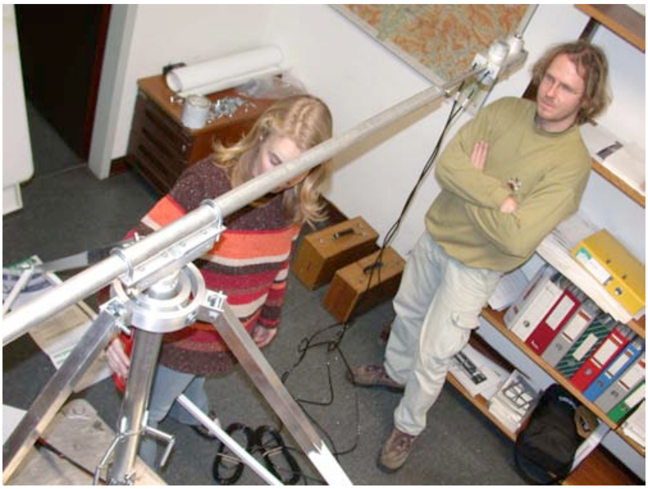

**Figure 2:** The cardan-like joint is the core of the self-adjusting mounting device (Foto: G. Kaser).

**Figure 3:** The installation of the AWS on Glaciar Artesonraju under harsh weather conditions in March 2004 (Foto: Robert Gallaire).

## First results

The self adjusting AWS mounting device was installed on the tongue of Glaciar Artesonraju in the Cordillera Blanca at 4800 m a.s.l. during a field expedition in early March 2004. Weather conditions were harsh and unpleasant for those who did the job, but ideal for an immediate test and evaluation of the functioning of the new mounting device (Figure 3). Wind was strong and very gusty with peaks up to more than 20 m s-1 and short calm periods. As weight for the pendulum, two boulders of together ca. 50 kg were used. On one jib, a radiometer was mounted, on the other arm two sonic ranging sensors provide information on both snow accumulation and, in addition to the clino-meter records, on the position of the device (Table 1). Logger and batteries were put in an aluminium case, which was connected to the device by cables. Solar panels were mounted on top of the box. On its bottom, the box was provided with crampon like spires to keep it on a fixed position close to the instrumental tripod.

**Table 1:** Instruments mounted at the AWS.

| Measured parameter | Instrument | Manufacturer |
|---|---|---|
| Radiation | Kipp&Zonen CNR1 | Campbell Scientific |
| Inclination | 2-axes Inclinometer | Sommer GmbH&Co KG |
| Accumulation/Inclination | Ultrasonic deph sensor | Judd Communications |

No matter how strong and gusty the wind was, the entire mobile device remained horizontal all the time. The site was visited twice within the following days and no problems occurred. We plan to revisit the Artesonraju site by beginning of July 2004.

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Wagnon, P., Ribstein, P., Francou, B. and Pouyaud, B., 1999: Annual cycle of energy balance of Zongo glacier, Cordillera Real, Bolivia. Journal of Geophysical Research 104, 3907-3923.

# MEASURING TURBULENT HEAT FLUXES ON MORTERATSCH-GLETSCHER, SWITZERLAND, WITH A SONIC ANEMOMETER

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## Introduction

In 2002, the Institute for Marine and Atmospheric Research Utrecht (IMAU) placed a sonic anemometer on the tongue of Morteratschgletscher (Figure 1). The aim was to measure turbulent heat fluxes throughout an entire year, and to compare these fluxes to bulk fluxes calculated from data of an IMAU automatic weather station (AWS). We placed the sonic a few meters away from this AWS. The sonic anemometer measured at 1.95 m above the surface in summer and during winter at variable heights, with a minimum of 0.6 m due to the presence of snow. The sonic was directed to the south, in upwind direction (which is glacier upwards). From the AWS data, we concluded that a glacier wind was usually present (directional constancy = 0.77). The sonic anemometer measured from 4 July 2002 until 18 June 2003. The sample frequency was 8 Hz. We applied online data reduction in order to obtain data over a longer period. The data logger only stored 10-minutes averages, variances and covariances of the three wind components, the temperature measured by the sonic and the temperature measured by a thermocouple.

**Figure 1:** Sonic anemometer on the tongue of Morteratschgletscher.

## Sonic anemometer tilt correction

Since the alignment of the sonic instrument was not parallel to the glacier surface, a correction for the tilt was necessary. We rotated the axes based on the measured velocities following two methods: the classical method and the planar fit method (Wilczak et al., 2001) and studied the results. The classical method rotates the coordinate system for each individual sample along the three angles in such a way that the average v, w and v'w' become zero. Due to statistical errors in the velocity measurements, this could however lead to a wrong rotation. The planar fit method rotates the coordinate system around the two horizontal axes at once. These angles are calculated from a series of samples, for instance from a day or a week. The alignment of the sonic should not change within this period and the tilt angle should not depend on wind direction for this method to work. Figure 2 shows the raw sensible heat flux as measured by the sonic and the corrected fluxes using the classical tilt correction and the planar fit correction (we calculated the tilt angles from data of one week). According to the results, the classical method causes an increase in the fluctuations of the sensible heat and the planar fit method causes a smoothening of the raw data. The corrected fluxes of the classical method are often positive (a flux from the surface towards the atmosphere), which is not in agreement with the fact that the surface temperature was always lower than the air temperature. The difference between the results of the two tilt correction methods is large: 22%. It seems that the planar fit method yields more accurate fluxes than the classical method. In any case, a correction for the misalignment of the sonic anemometer on Morteratschgletscher is necessary.

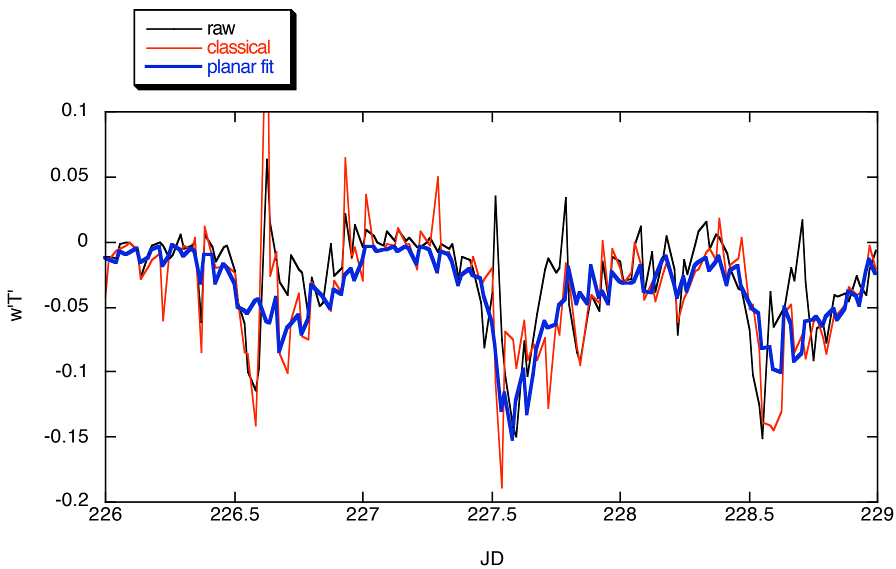


**Figure 2:** Sensible heat flux as measured by the sonic anemometer (raw) (ms-1K), and after tilt correction using the classical and the planar fit method. The data are for three summer days in 2002.

## Bulk and sonic anemometer heat fluxes

We then calculated the sensible heat flux from the AWS data using two different bulk methods: The first one uses a constant turbulent exchange coefficient of 0.00153 (Oerlemans, 2000). The second uses a turbulent exchange coefficient that depends on the stability of the atmosphere. We used the stability functions of Beljaars and Holtslag (1991) and varied the surface roughness length (z0) between 0.5 and 1.0 cm. Averaged over the entire measurement period, the sensible heat flux measured by the sonic, after alignment correction following the planar fit method, is 22.1 Wm-2. The bulk method using a constant turbulent exchange coefficient leads to an average heat flux of 32.0 Wm-2. When the stability of the atmosphere is taken into account, the average sensible heat flux is 31.9 Wm-2 (for z0=1 cm) and 30.1 Wm-2 (for z0=0.5 cm). The sonic sensible heat flux is about 27% smaller than the fluxes derived from the bulk methods. Especially during summer and at daytime when a glacier wind is present, differences between the sonic and the bulk fluxes are large. Figure 3 shows the sensible heat flux measured by the sonic anemometer and calculated from the AWS data with the bulk methods for three summer days.

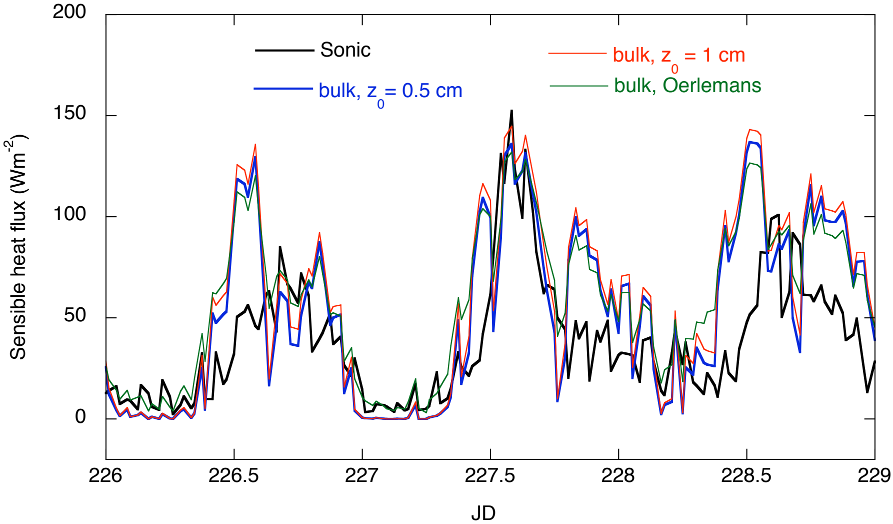


**Figure 3:** Sensible heat flux as measured by the sonic anemometer after tilt correction using the planar fit method, and calculated from the AWS using a bulk method and a constant turbulent exchange coefficient following Oerlemans (2000), and stability correction functions varying z0 between 0.5 and 1 cm. The data are for three summer days in 2002.

The sonic anemometer seems to underestimate the sensible heat flux. This could be because it measures in or close to the wind speed maximum of the glacier wind. Other explanations are the presence of gravity waves or other non-local fluxes that occur due to the surrounding topography (Denby, 1999). However, it is difficult to state whether the bulk method or the sonic measurements approximate the turbulent heat fluxes best. For this, we would need to study the accuracy of the measurements and the other energy balance components in more detail.

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# AUTOSTATIONS NETWORKS IN THE CANADIAN ARCTIC ARCHIPELAGO: - TWENTY YEARS LATER, ISSUES AND PROBLEMS

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## Introduction

Mass balance studies of glaciers and ice caps in the Canadian High Arctic Archipelago have been ongoing for over forty years (Koerner, 1996) In perspective, continuous long term instrumented climate records go back to barely sixty years. Auto stations, apart from earlier but brief successes, were running unattended in this area by the late 1970's. In 1987, an initial government/industry partnership, led to a longer-term collaboration between Koerner and Labine. As a result, we have one of the longer auto station records for a polar ice cap. We are all familiar with the challenges of these environments. It is comforting to see all the similarities of our common problems. More so, it is the similar and diverse solutions we bring to these challenges, which are worth sharing at this workshop.

Our initial goal was to be able to maintain an auto station under those conditions and with only a yearly site visit. Furthermore, we wanted to keep the systems as simple as possible. Finally, we in Canada among the polar scientists in the circumpolar world (except perhaps for post Soviet Russia), have to work with some of the smallest and seemingly ever decreasing budgets.

**Table 1:** Locations of Automatic Weather Stations

| DEVON ICE CAP<br>Devon Island, Nunavut | Latitude | Longitude | Elevation |
|---|---|---|---|
| Top: (D1) | 75.34°N | 82.02°W | 1900 m |
| F: (D2) | 75.39°N | 82.76°W | 1768 m |
| D: (D3) | 75.42°N | 82.95°W | 1628 m |
| ICS:(D4) | 75.49°N | 83.28°W | 1339 m |
| Sverdrup Glacier: (D5) | 75.69°N | 83.26°W | 330 m |
| MEIGHEN ICE CAP<br>Meighen Is., Nunavut | 79.96°N | 99.14°W | 250 m |
| MELVILLE ICE CAP<br>Melville Is., Nunavut | 75.46°N | 114.99°W | 715 m |
| AGASSIZ ICE CAP<br>EllesmereIs., Nunavut) | 80.8°N | 72.88°W | 1800 m |
| | 80.83°N | 71.92°W | 1338m |
| | 80.87°N | 71.29°W | 878 m |

To date we have met these goals and are able to maintain a small network of local stations on four of these ice caps and for some of their offspring glaciers. Table 1 shows the location and distribution of these stations. We continue the collaboration and we are pleased to be able to share our experiences with you. The basic goal of our research is to provide a record to complement the annual mass balance work and also be able to provide a better and more complete description of the climate for the entire year.

## Methods and materials

In light of our intent to keep the stations as simple as possible, most of the stations have only an air temperature sensor as well as an ultra sonic snow depth sensor. These are the most effective measurements given the nature of the ongoing research. They certainly represent two parameters, which are probably the least prone, relatively speaking to measurement problems in these environments. Wind speed and incoming solar radiation are two other parameters, which we originally measured. However, given the problems associated with riming and snow accumulation, the potential for data loss of these parameters was too great. There certainly are solutions to being able to measure these at present, but they still invariably require more electrical power consumption and more frequent site visits. The latter is not very possible given the decreasing budgetary resources. Larger power supplies are possible but up until recent years were still too bulky and expensive. Since we do not need real time date, we have no remote communication systems with these stations. Some of the existing satellite systems do not offer two-way communications, do not operate at those latitudes, or consume too much power. Quite honestly the service providers have not all been stabile enough to warrant the expense of this, for us, communication luxury. Again, there are some positive signs in that industry and we plan to eventually have a two-way communications system. At the very least, it would be useful to call a station prior to the field season in order to get a status of the various components. Even though we don't need real or near real time data, it would be comforting to be able to regularly download data at more regular intervals than once per year.

**Table 2:** Equipment Details of Automatic Weather Station

| |
|---|
| Data acquisition and control system - Campbell Scientific CR10X-55 |
| Power Supply – Gates or Panasonic 26 ampere/hour battery (BP26) |
| Solar Panel for charging BP26 (Solarex 10 Watt Panel) MSX10 |
| Air Temperature Unventilated – CS 107F Thermistor Probe |
| Shield for Unventilated Sensor – RMYoung Gill Radiation Shield 41042 |
| Air Temperature Ventilated – Chromel Constantan Fine Wire Thermocouple |
| With CS 107F thermistor as reference temperature on wiring panel of CR10X |
| Shield for Ventilated – CS ASPTC Aspirated Shield (Fan air velocity 5.5 m/s) |
| Snow Depth Sensor, Campbell Scientific Canada SR50, Ultrasonic Sensor |

Table 2, lists the sensors and equipment used. As much as possible we have tried to follow the guidelines for auto stations set out by Environment Canada (Anonymous, 1992). In the early years, this was not always possible, not only because of our self-imposed constraints (simplicity, small power supplies) but also given the limited budgetary resources. At first, the limited capacity of data storage memory was a limiting factor. Even though memory capacity is no longer a limitation, there are still some data outputs recommended by Environment Canada, which we do not produce. Their time scales are meant for real time forecasts and do not have bearing on the time scales of the processes we are investigating.

At the heart of each station is a Campbell Scientific CR10X data acquisition and control system. These are designed to operate down to –55°C and they have very low power consumption. For the moment, our power supply consists of a single 10-watt solar panel and a 26 amp-hour battery. The sensors are maintained at a height of approximately 1.5 meters. The heights are adjusted during the annual site visit. For accumulation areas near the summits, this means that the sensors are moved up the support mast or the mast is extended.

As time and resources are allowing, we are gradually adding a few more elements. We want to add a few more parameters not necessarily for the mass balance research but mostly to assist in quality control of the information. The main concern we have is with the quality of the air temperature measurement. Initially we used a Stevenson Screen, but that proved to be problematic because it would invariably fill up with snow (see Figure 1). We then switched to the small Gill self-aspirating shields. Although these work well when the wind is blowing, under calm conditions and high radiation loads, heating of the sensor can occur. As mentioned, incoming solar radiation and wind data are being added to assist with the quality control of the data, especially the air temperature data. We have also added, a small aspirating shield and temperature sensor. To keep our power consumption low, we only activate the fan, during the last ten minutes of the hour and we limit the fan use to the period from April to September. This is the period where most of any potential errors due to radiative heating will occur. We should be ventilating the sensor throughout the year, but given the power considerations, have chosen to limit this to the more critical "polar day" period.

**Figure 1:** Stevenson screen after over-wintering.

## Today's Issues and Concerns

Each instrumented parameter has it's own inherent potential difficulties but in this environment we face the common problems of low temperatures, riming and icing, and for polar regions, no solar radiation for recharging batteries for part of the year. We have certainly resolved the issues of continuous automatic year round monitoring. Our data recovery rates are generally high as we are seeing within this entire community. The emphasis now is to know the quality of our data and to be able to identify instrumentation and technique errors. In our case, given single annual visits, the potential for a whole year of missing data is still possible. For example Figure 2 shows our temperature record to date. These are expressed as monthly means and apart from showing the general conditions of the station, also show two data gaps. Our main concern is with the accuracy of the air temperature measurements. With the recent addition of an aspirated sensor, we think we have a better measurement of temperature since we do not have the concern of potential heating as usually seen in an un-aspirated radiation shield.

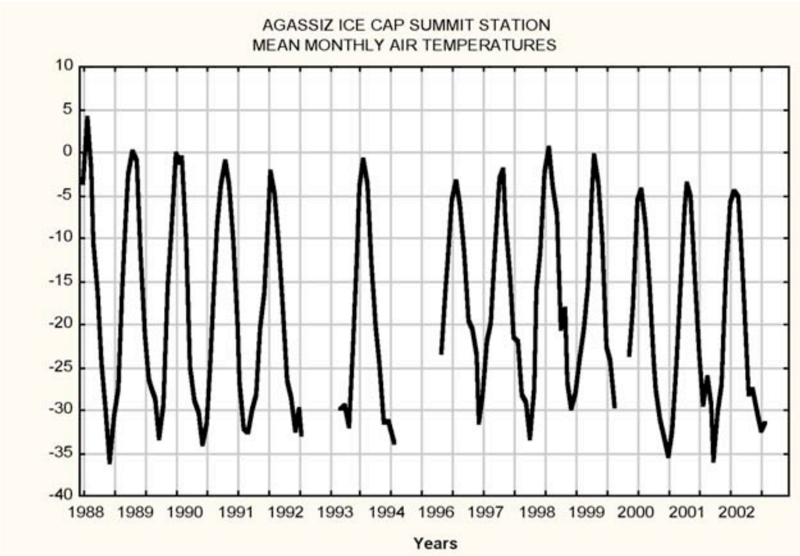


**Figure 2:** Mean monthly air temperature.

Figure 3 shows the most recent available data, which compares the aspirated and non-aspirated shields. On a daily basis, the two measurements track very well. The early spring period shows the greatest frequency of differences. This period is characterized by clear and calm conditions, which means that the unventilated shield will potentially experience the greatest amount of self-heating. Figure 4, shows the actual temperature difference between these two measurements. As can be seen there is the potential for some daily temperature readings to be in excess of 3°C, albeit infrequently. For the majority of time, the difference between the two types of shields is slightly less than 1°C. A recent evaluation of temperature and humidity sensors as well as various shields (Beaney et al., 2004), conclude that “preliminary results indicate that the type of non-aspirated screen used does not appear to have a significant impact on temperature sensor performance”. Although this is comforting news, our results indicate that we need to continue this evaluation and quality control of our air temperature measurements.

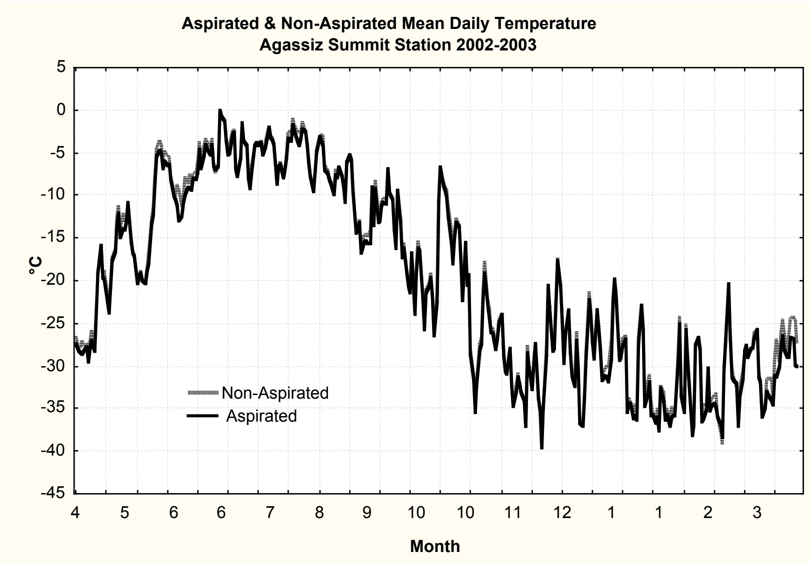


**Figure 3:** Daily mean air temperatures.

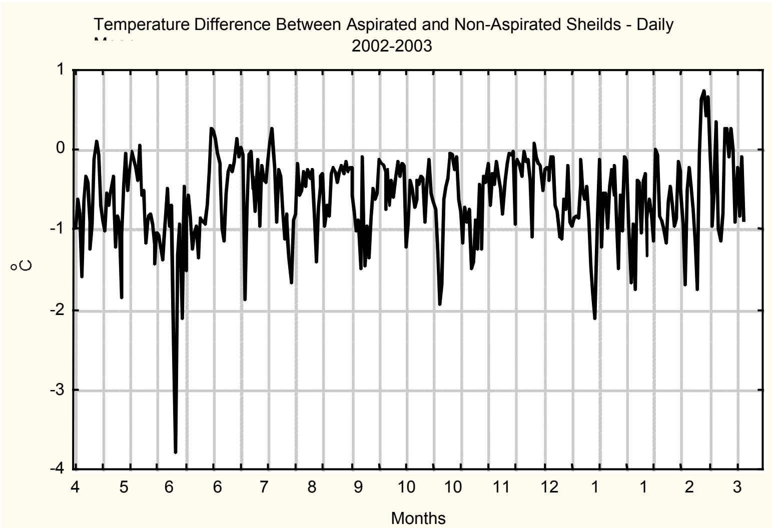


**Figure 4:** Mean daily temperature difference, ventilated vs. non-ventilated.

Snow depth measurements are an integral part of a mass balance study. Figure 5 shows some of the early results from three of the stations on Agassiz Ice Cap. The main feature we wish to point out, is that we really are not used to continuous measurements of snow depth. The data show that this parameter is quite dynamic and can be quite variable. Most of the variability of the measurement can be traced to the re-distribution of snow by wind, the settling of snow after the initial snowfall event and finally during the “summer” period, to the melting or sublimation of the snow pack.

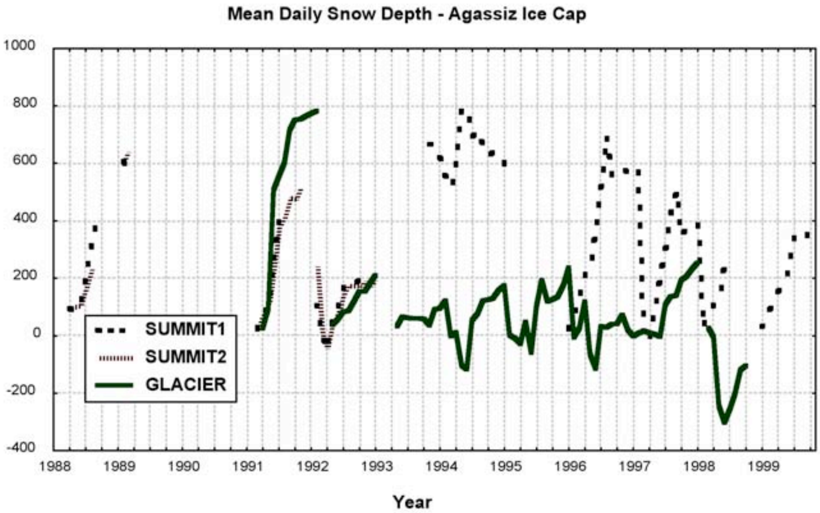


**Figure 5:** Mean daily snow depth.

## Non-Instrumental Issues

A long term monitoring program has other requirements beyond equipment related issues, which need to be in place in order to maintain a proper database. As in most programs associated with auto-stations, the two most important non-equipment issues are documentation and quality control of the data. Beyond the usual station documentation, the metadata of the station needs to be as complete as possible especially given the increase in exchange and sharing of climate data. It follows that as we share our data, we need to be able to properly describe the limitations and accuracies of the data in order for others to use it correctly.

Finally, as indicated previously, a unique Canadian problem has been the funding or more accurately the lack of funding of science research in the Canadian Arctic. In these past few years, other countries have been spending more money on research in Canada than Canada itself. This issue is not directly related to auto-station issues, but it certainly is part of the reality that we face as researchers. Although the budgetary climate is still poor there have been recent advances made we a commitment by the present government to improve the situation of funding for the Canadian Arctic.

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# OPERATING THE AWS AT WESTERN CANADA GLACIER SITES

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The automatic weather station (AWS) program for Western Canada glaciers is a work in progress since the installation of the first AWS at the Geological Survey of Canada (GSC) base camp site adjacent to the Peyto Glacier, in September of 1987 (Figure 1). After a few years of trial and error, marked by data interruptions, the station evolved into a reasonably reliable collector of hourly global (solar) radiation, air temperature, relative humidity, wind speed and direction data. Precipitation data have been more problematical, though prospects for this appear to be better, now that a load-cell gauge has been installed. Other data include surface temperature, atmospheric long-wave radiation and occasional pyrheliometric measurements of direct solar radiation.

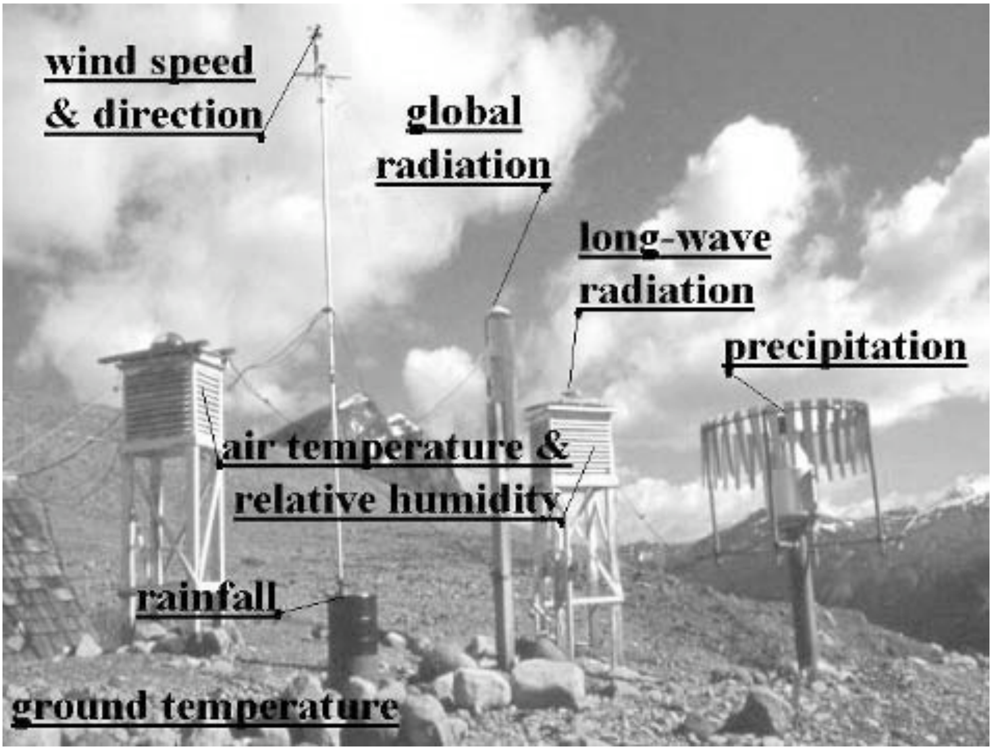


**Figure 1:** Peyto Glacier base camp AWS station, est. Sept. 6, 1987.

More recently, GSC base camp AWS measurements have begun at the Place Glacier, August 2001, and at the Ram River Glacier, July 2003, as the meteorological side of the GSC National Glacier Program continues to expand. Despite severe financial constraints, development of the program has been possible due to collaboration among the GSC, the University of Toronto and the University of British Columbia, where research funding has been gathered from various sources over the years, among them the Natural Sciences and Engineering Research Council of Canada, but most currently through the Cryospheric System (CRYSYS) to assess global change in Canada, a program of the Meteorological Service of Canada.

The establishment of glacier AWS sites has proven to be more of a challenge due the seasonal extremes of the mass balance cycle. The first such AWS was set up on the tongue of the Peyto Glacier, September 1995, beginning with air temperature. This has since expanded into a station, such as briefly stood near the equilibrium line of the Place Glacier (Figure 2), where measurements include incoming global and reflected short-wave radiation, air temperature, relative humidity, snow and ice temperatures, wind speed and, through the use of an acoustic sounder, height above snow or ice. The goal for the Peyto Glacier is to expand beyond the glacier tongue, placing additional AWS sites near the equilibrium line and near the top of the glacier accumulation zone. For the smaller Place Glacier, it is believed that an equilibrium line AWS will suffice.

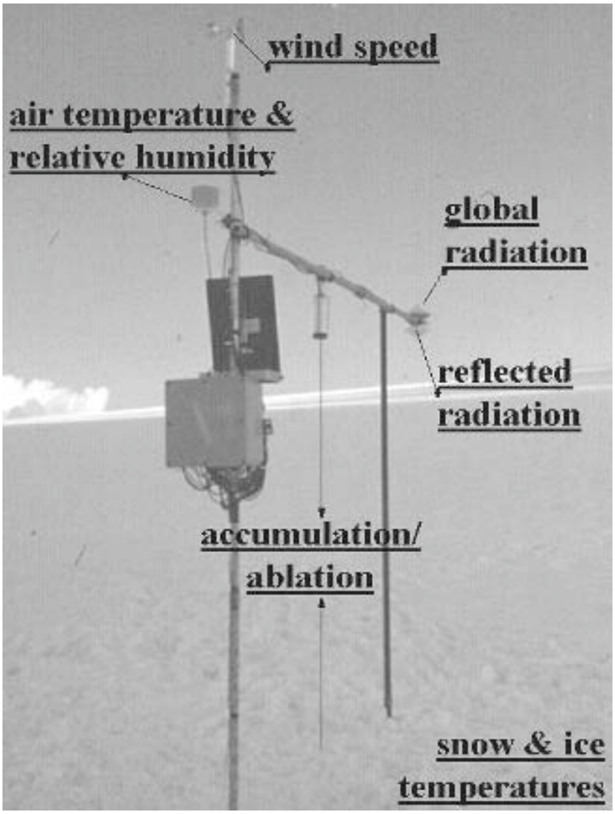


**Figure 2:** Place Glacier AWS, July 2002 to June 2003.

The greatest degree of success has been with the Peyto tongue AWS where, after some frustration with the drilled-in design of Figure 2, the decision was made to modify a floating design which had been effective in the past for micrometeorological experiments. The nature of the modification is to dispense with the use of guy wires, choosing instead to mount the vertical supports on feet attached to rocks that happen to melt into the ice at the same rate as the ice itself melts. The exception is the acoustic sounder. It is mounted on a tripod structure, the feet of which are drilled into the ice. This works well, provided the sensors are mounted sufficiently far above the surface to avoid being covered by the winter snowpack, which for the Peyto Glacier tongue, rarely amounts to more than 1.5 m thick. Because it is not easy to frequently visit the site, the design provides protection against instrument loss due to melt-out of the support structure, the worst that can happen being the loss of ablation data from the acoustic sounder until such time as the supports can be re-drilled.

A drilled-in design for AWS sites near and above the equilibrium line is perhaps suitable because, near the equilibrium line one might expect considerable periods of time to pass before remounting of sensors is necessary, while in the accumulation zone it might be possible to continue with extensions to the support structure. However, near the equilibrium line there have been problems due to snow loading on the horizontal parts of the mounting structures: bending of pipes for snow cover of ~0.5 m or less; damage to instruments and shearing of shields and data logger boxes from vertical supports for overlying thickness > 0.5 m. Equilibrium area snowpack thickness is in the order of 3 m for the Peyto, 6 m for the Place.

One response to increasing snowpack thickness is to extend the heights of the sensors, an approach which becomes increasingly risky for free-standing structures as height increases. Attempts to do this were made at both the Peyto and the Place. When we returned to the Peyto equilibrium line two months later, to find the structure collapsed on the ice, one thought was to ascribe the damage to attempts by visitors to climb the structure because the area is heavily used for hiking and ski touring. Discovery of the same consequence for the Place Glacier AWS, where there are few visitors to the glacier itself, poses an alternative: metal fatigue due to oscillation in a von Kármán vortex street.

One way to deal with this may be through the use of guy wires, an option which we are successfully using for the Peyto accumulation zone AWS, where the winter snowpack is approximately half that of the Place Glacier. Alternatively, for thicker snow cover, it may be possible to a free-standing triangular tower fastened to pipes drilled into the ice and to mount solar panels, batteries and data logger boxes in such a way as to minimize wind resistance. Regarding design safety, it should be noted that if support structures becomes easy for visitors to climb then they are likely to do so, risking damage to the station and personal injury.

Instrument deployments are advised by modelling needs perceived from the literature1. Thus it appears that solar radiation, air temperature, relative humidity, wind speed and direction, and precipitation, are the basic requirements for a base camp AWS, as those would play the role of driving parameters. On the glacier itself, AWS sites which yield validation data are needed: air temperature, relative humidity, snow and ice temperature, wind speed, and height change due to ablation or accumulation. Incoming and reflected short-wave radiation should be measured at whichever AWS experiences the greatest change in surface cover over the year. An hourly data acquisition interval is used for our stations, that being judged to be suitable for glacier hydrology purposes.

In addition to providing a key driving variable for modelling, global radiation data are also proving to be useful in calibrating a bulk radiation model that we use for Landsat Thematic Mapper image analysis. Data from the new load-cell gauges appear to yield realistic precipitation estimates when a suitable filtering protocol is applied to the signal, prior to making corrections for under-catch and evaporation loss. There is concern about finding suitable off-glacier AWS locations, such that air temperature measurements are representative of the air mass surrounding the glacier. It seems that the Peyto Glacier AWS (Figure 1) is well situated in this respect, but that the off-glacier location of the Place Glacier AWS is unduly influenced by the glacier cooling effect.

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# ON THE PERFORMANCE OF UNASPIRATED, PLATE-SHIELDED THERMOMETER SCREENS

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## Background

Temperature sensors can well be calibrated with respect to internationally approved standard procedures (laboratory calibration). It is known, however, that the *field accuracy* of meteorological temperature measurements largely depends on the kind of shields used to mount and protect the sensor. With the exception of the well known Stevenson screen, such shields are not subject to any kind of internationally approved standardization (Guide to Instruments and Methods of Observation, WMO, No.8) and there exists a corresponding wealth of different devices. The associated discrepancy is pending due to the enhanced use of automatic weather stations and the rapidly developing and changing markets.

This contribution focuses on the performance of plate-shielded screens for temperature measurements on automatic weather stations. Such have been derived from the well known Stevenson screen and they are available in different sizes and designs. Naturally as well as artificially ventilated versions are in practice, of which the former is of special interest as often used in remote areas due to associated power constraints (e.g. glaciers). This study is based on a compilation of manufacturer's specifications, literature references, own experiences and a new development on the market. A special emphasis is on the frequently used R.M. Young type shields.

Principally, temperature measurements are influenced by a number of environmental circumstances, as there are (van der Meulen, 1998):

- Direct radiation by the sun (by day) on the sensor.
- Indirect radiation (after reflection by the ground, water surface, snow or the screen itself) form the sun on the sensor.
- Direct and indirect infrared radiation by the screen itself and from outside the screen (ground, water surface, snow) on or from the sensor (i.e. there is no balance in IR radiation heat transfer).
- Insufficient natural or artificial ventilation of the air inside the screen with the air outside causing typical micro-climate effects and long response times.
- Non-natural mixing of the air around the screen caused by local artificial ventilation or wind shields.
- Cooling of the screen and the sensor caused by precipitation (rain, showers, drizzle and snow will cool down the screen) or wetting by aerosols (during precipitation and fog) of the (day bulb) sensor. The sensor may act as a wet bulb sensor as a result, typically is case of strong winds, or ventilated shields. Moreover, snow and ice on top or around the screen and collection of water inside the screen (evaporation) will cool down the air inside the screen.
- Shadowing due to obstructing objects (masts).
- Convective effects due to strong heating of the stand caused by absorption of solar radiation (moraines).

- A special issue is wind. In case of no wind at all the natural ventilation of the air inside the screen is limited to diffusion only. The effects stated above will be more significant than in case of strong winds in combination of precipitation the sensor inside the screen will be affects by deposition of aerosols or small droplets.
- Contamination and degradation of the screen e.g. due to dark pollution.

Thus, screens inevitably introduce inside micro-climate effects, which principally can be assessed by intercomparison measurements using well calibrated sensors and different shieldings. There is a corresponding question about the definition of a standard screen, which may act as a reference. As refers to the plate-shielded screens, a limited number of intercomparison measurements is documented, mostly in internal reports and taking a Stevenson screen as a reference.

## Results of intercomparison measurements by companies and national weather services

A long-term intercomparison of seven different screens was performed from 1989 to 1995 at the instrument test site at KNMI in De Bilt, the Netherlands (van der Meulen, 1998). Every 15s a temperature sample was registered together with wind speed, global radiation and precipitation. The measurements were carried out 150cm above well cut grass unless when snow covered the ground.

Based on the analysis of this six years dataset, it was found that the long-term average temperatures in synthetic screens agree to a reference within 0.2°C. However, daily minimum and maximum temperatures differed from screen to screen. There was a systematic long-term seasonal variation in the differences of about 0.5 (in winter) to 1.0°C (in summer). Under particular circumstances larger deviations exceeding 1°C were found. As a side result, the standard Stevenson screen was shown to suffer from significant self heating as well (+1.5°C with $800Wm^{-2}$ global radiation and wind speeds less than 2m/s).

The more detailed studies confirmed that impacts of radiation, wind, rain, dew-deposition should be considered in the first place for any design of screens. It is the specific combination of these parameters that makes the final difference. However, it was found that many larger differences are caused by short-term fluctuations in and around the shelter, i.e. by micro-climatological (turbulence) effects, which are not directly related to the particular design of the screen. Moreover, the effects of moisture and condensation as well as of sunshine on different parts of the shield are addressed as well. However, the study does not address specific problems when measuring above snow or ice and the R. M. Young type shield is not mentioned as an exceptional design.

Huband (1990) performed another comparative study of radiation shields. Three shield designs (including a R. M. Young type) were considered, which were exposed over short grass alongside other standard meteorological instruments. The readings were recorded as 5 minute averages of samples made every minute and a 3 month period during spring and summer 1989 is considered. Again, the plate-shielded temperature readings fluctuated more strongly than that measured within the Stevenson screen. This was attributed to the larger size and restricted airflow through the Stevenson screen giving rise to a larger time constant. Moreover, the maximum temperature in all shields occurred at the same time but minimum temperature tended to occur slightly later in the Stevenson screen, especially on calm nights. In general, the agreement between the various shield designs was better than ±0.5°C. As regards a R.M. Young type shield, 78% of readings obtained with a lay within ±0.2°C of screen temperature. On occasion, however, each design of shield produced temperature measurements differing by more than ±1°C from those measured in the standard screen. These deviations were mostly related to periods when air temperature was changing rapidly and thus may be caused, in part, by the different response times. Further, the temperature differences showed a weak diurnal pattern with screen temperature exceeding shield temperatures around the time of the minimum and shield temperature exceeding screen temperature around the time of the maximum temperature. As regards the wind effect, the temperature differences were significantly greater (>1°C) at wind speeds less than $1ms^{-1}$. Spot measurements using the Assmann psychrometer yielded agreement within ±0.8°C of the Assmann value. The R.M. Young type shield is not mentioned to behave exceptional in this context. It is mentioned, however, that shields with a more open design are likely to lead to significant temperature errors when exposed over snow surfaces.

Another study refers to a comparison of temperature readings in two passively ventilated (including a R.M. Young type) and three fan-aspirated radiation shields under conditions of low wind and relatively high insolation (Davis, 2004). The units were mounted above irrigated close-cropped grass and positioned such that no shield was wind-shaded with respect to the prevailing direction. The two days considered were characterized by wind speeds less than $2ms^{-1}$ and direct solar insolation ranged between 800 and $1200Wm^{-2}$, respectively. A first series of exemplifying data considers daylight hours only and indicates that the unaspirated designs yield systematically higher temperatures than measured in the aspirated shields. Their excess temperatures range from 1.4 to 6.4°C, the latter being valid for the R.M. Young shield. The authors note lag phenomena indicating different time constants of the designs. A second series reveals that the unaspirated temperatures were 0.8 to 3.0°C higher than those measured in the aspirated shields. Thus, this study indicates that the unaspirated R.M. Young design can seriously suffer from combined wind and radiation errors.

An Austrian company (Kroneis, 1993) performed intercomparison measurements during 21 clear days involving a Stevenson screen and five alternative shielding devices (aspirated and unaspirated, including an R.M. Young model). At the time of maximum temperatures there was an average span of 1.5°C between the individual readings as compared to 0.5°C at the time of minimum temperatures. On average, the readings from the R.M. Young design compared within several tenths of a degree to those from the Stevenson screen. However, the latter both read on average about 1°C higher than the artificially ventilated screens. These effects were generally less pronounced during night.

## An own experience

In the context of energy budget investigations of an Alpine snow pack, temperature intercomparison measurements were performed using a well shielded and artificially aspirated device (Kroneis 430M) and a R.M. Young shield on the other hand (Obleitner, 1999). Figure 1 demonstrates an extreme situation when during the late morning hours of the second day the temperature recorded within the unaspirated R.M. Young shield was 8.5°C higher than measured in an artificially aspirated shield. The effect is obviously relatd to high solar insolation and wind speeds less than 0.5ms$^{-1}$. Because of the presence of new snow below the instruments, however, a large amount of reflected solar radiation must have impinged on the shields additionally. Due to the inclined orientation of the plates, this reflected solar radiation can easily penetrate to the interior and thus directly affect the sensor. This situation resulted in disturbances larger than 1°C for a period of almost six hours, which coincides with wind speeds less than 1ms$^{-1}$. The experience indicates that the "normal" extent of temperature errors (<1°C) of unaspirated plate-shielded devices can be extremely enhanced if a bright snow cover is present below the instruments. This is an important issue in the context of glaciological applications as well.

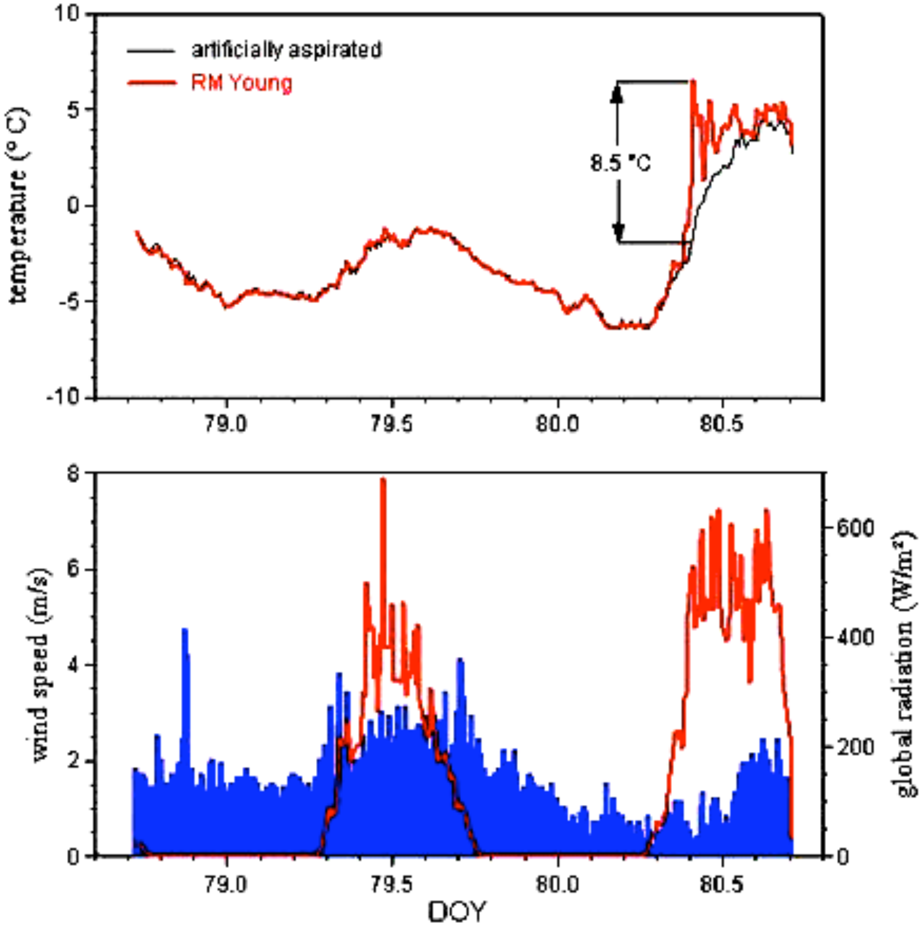


**Figure 1:** Measurements of temperature in an artificially aspirated (Kroneis 430M) and in a plate shielded (R.M. Young) device. The lower panel indicates wind speed and global radiation as measured at the site (Obernberg, 1999).

## On a new development

Recently, a modified plate-shielded device has been introduced i.e. the Vaisala, DTR500 series (Vaisala, 2004). The special aspect is that the inside (lower) surfaces of the shields are painted in black. The effect is described to absorb accumulated heat and to protect the probes from scattered radiation as well. On request, there was no quantitative specification of the anticipated effect available.

Interestingly in this context, a corresponding study has been performed elsewhere ten years before (Schmittner, 1994). This is based on parallel temperature measurements using well calibrated thin-wire thermo-elements displaced in a Stevenson screen and in two R.M. Young type shieldings. One of the latter was original (sensor 1) and the other's down facing surfaces were painted in black (sensor 2). The measurements were evaluated for clear days in September 1993, when the air temperatures reached 30°C and global radiation reached $350 Wm^{-2}$ at noon. The results demonstrate a distinct response of the two different devices. With only $200 Wm^{-2}$ insolation and wind speeds up to $2 ms^{-1}$, for example, an average excess temperature of 2.3°C (sensor 1, Figure 2a) and 0.75°C (sensor 2, Figure 2b) was recorded in comparison with the measurements in the Stevenson screen. It may be mentioned here that these figures are in striking contrast to the manufacturer's specifications suggesting e.g. 1.5°C errors with $1080 Wm^{-2}$ and wind speeds less than $1 ms^{-1}$ (R.M. Young, 2004). The measured excess temperatures are linearly related to global radiation and there is a systematic difference between the morning and afternoon hours, which can be related to accordingly different wind conditions (stronger winds in the afternoon) affecting the naturally ventilated shields. Increasing wind speeds reduce the effect, which can be fitted by an exponential function (Figure 2c). During night, the plate-shielded devices cooled more effectively than the Stevenson screen, which was in an extent of –0.5 to -0.8°C and independent of the colour of their down facing surfaces. Based on these investigations, correspondingly calibrated correction formulae as functions of solar radiation and wind speed were developed for both devices. Of course, it is to be questioned in what extent these quantitative results can be generalized or be transferred to the mentioned Vaisala DTR500 products. However, the results of this study are highly indicative that blackening the down facing surfaces of plate-shielded thermometer screens is an inexpensive means to effectively improve the measurements. Qualitatively as well, a positive effect could be expected with regard to measurements above snow or other surfaces with a high albedo.

## Conclusions

A quantitative investigation of the performance of screens for temperature measurements on automatic weather stations is complicated by the great number of processes playing a role and by the variety of existing constructions on the other hand. Moreover, much of corresponding experience is probably not documented or hidden in internal reports. It is clear, however, that practise always runs towards a compromise to properly mount and mechanically protect the sensors, to provide unrestricted airflow across the sensor, to minimize radiative exchange and to adjust to logistical (e.g. power) constraints. Thus, most screens inevitably introduce inside micro-climate effects impinging on the sensors. Intercomparison measurements are the only tool to judge the performance of individual devices, which in lack of an absolute standard often refer to the Stevenson screen.

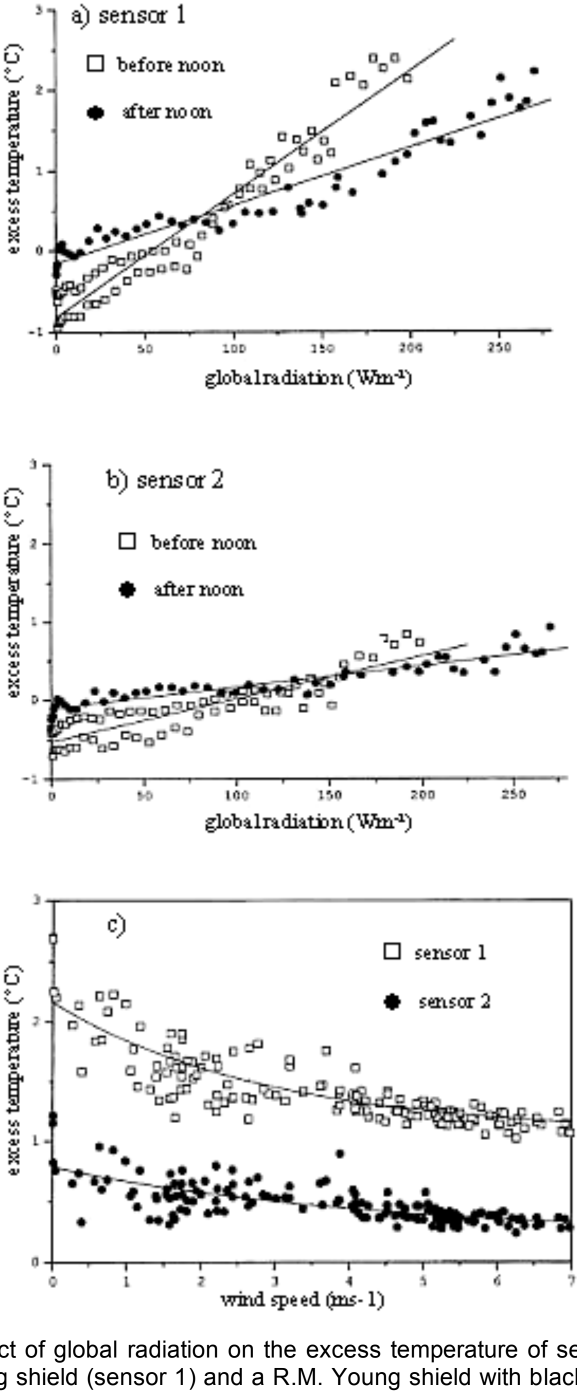


**Figure 2:** The effect of global radiation on the excess temperature of sensors inside of an original R.M. Young shield (sensor 1) and a R.M. Young shield with blackened down facing surfaces (sensor 2). The effect of wind speed on excess temperature measured within the two devices (relative to a standard Stevenson screen).

This contribution focuses on the performance of naturally aspirated and plate-shielded temperature screens, with special emphasise on R.M. Young-type devices. A compilation of corresponding investigations by manufacturers and official weather services indicates that the long-term average deviations against a Stevenson screen are usually within 1°C. Moreover, the various studies revealed systematic daily and seasonal effects resulting in generally smaller deviations during winter or at the times of minimum temperature, respectively. Part of these deviations could be related to different time constants of the devices, which plays an essential role when air temperature rapidly changes. Under particular circumstances, however, deviations of several degrees Celsius were repeatedly documented. These extreme events were always associated to meteorological situations with high solar radiation input and low wind speeds, the latter being critical for values below 1ms$^{-1}$. The presence of a bright snow cover was identified as a definitely enhancing factor. A further study demonstrates that based on thorough intercomparison studies the gross effects could potentially be corrected using parallel radiation and wind measurements. On the other hand this study also proves, that blackening of the down-facing surfaces of the plates of the shield has a high potential to effectively reduce the unfavourable effects, which has been put into practise by a newly introduced product on the market.

It is to mentioned finally, that radiation shielding is equally important in the measurement of humidity. For instance, where solid state humidity sensors are used, temperature changes in the sensing element will cause erroneous humidity readings and water retention by the shield after rain could give an artificially humid airflow across the measuring probe within the shield.

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# AWS IN THE ABLATION ZONES OF GLACIERS

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Different glaciers react in different ways to climate change, depending on specific glacier geometry and climatic setting. With the help of computer models such factors can now be dealt with. More and more, glacier models are used to study individual glaciers, understand their fluctuations in historic time, and make projections for future behavior if a specific climate scenario is imposed. The quality of model output depends basically on how correct the physical processes (e.g. ablation, accumulation, ice flow) are treated.

Especially the relation between meteorological quantities and the mass balance of a glacier surface has turned out to be a critical element in the modelling studies. To get a better hold on the processes that determine the amount of ablation, the Institute for Marine and Atmospheric Research, Utrecht University (IMAU), has conducted a number of detailed meteorological field studies. These studies (mostly in collaboration with other research organizations) have been carried out during relatively short periods in summer, operating many weather stations at the same time [Hintereisferner, Austria, in 1989, e.g. Van de Wal et al., (1991); West-Greenland in 1990, 1991, e.g. Oerlemans and Vugts (1993), Pasterze, Austria in 1996, e.g. Greuell et al. (1997); Vatnajökull, Iceland, in 1996, e.g. Oerlemans et al. (1997)].

Working with the data obtained in these experiments has made clear that longer series of measurements from ablation zones are also needed. Especially on larger glaciers, melting on the lower parts is not restricted to the summer season. A better calibration of mass balance models could be achieved if data over longer time periods would be available. However, using automatic weather stations on glaciers for longer periods of time has its difficulties. First of all, it is desired to keep the sensors at about a constant height above the glacier surface. When melt rates are large, this is not simple. When large amounts of snow are deposited on the surface, this is almost impossible. Secondly, there is no high-voltage power available. So instruments should have very little power use so that they can run on

**Table 1:** AWS currently operated by the IMAU in the ablation zones of glaciers.

| Location | Latitude and Longitude | Alt. (m) | $P_{ann}$ (m) | $b_n$ (mwe) |
|---|---|---|---|---|
| 1. W.Greenland-I | 67° 05.967’ N, 50° 06.803’ W | 475 | 0.3 | -4 |
| 2. W.Greenland-II | 67° 04.626’ N, 49° 23.017’ W | 1024 | 0.3 | -2 |
| 3. W.Greenland-III | 67° 03.039’ N, 48° 13.881’ W | 1467 | 0.3 | +0.2 |
| 4. Breidamerkurjökull | 64° 05.791’ N, 16° 02.900’ W | 275 | 4 | -10 |
| 5. Morteratsch-I, CH | 46° 25.531' N, 09° 25.531' E | 2116 | 1 | -6 |
| 6. Morteratsch-II, CH | 46º 24.491' N, 09º 57.322' E | 2640 | 1.6 | -2.5 |
| 7. Hardangerjökulen | 60° 34.243’ N, 07° 28.051’ E | 1449 | 3 | -4 |
| 8. Storbreen | 61° 34.545’ N, 09° 09.482’ E | 1658 | 2 | -3 |

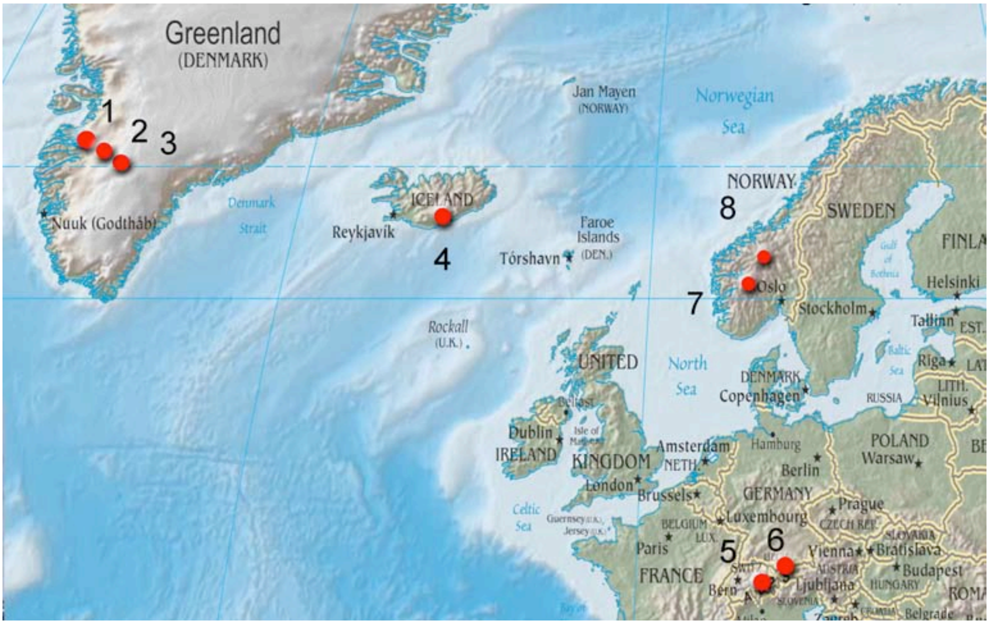

**Figure 1:** AWS currently operated by the IMAU in the ablation zones of glaciers.

a simple solar panel (with a battery). Thirdly, outside the summer season the conditions are humid and cold, making the functioning of sensors more critical.

At IMAU weather stations have been developed that can operate unattended for a considerable period of time. The quality of the data is always less than that of manned stations, but after ten years of experience we are convinced that very useful data on the basic meteorological quantities can be obtained.

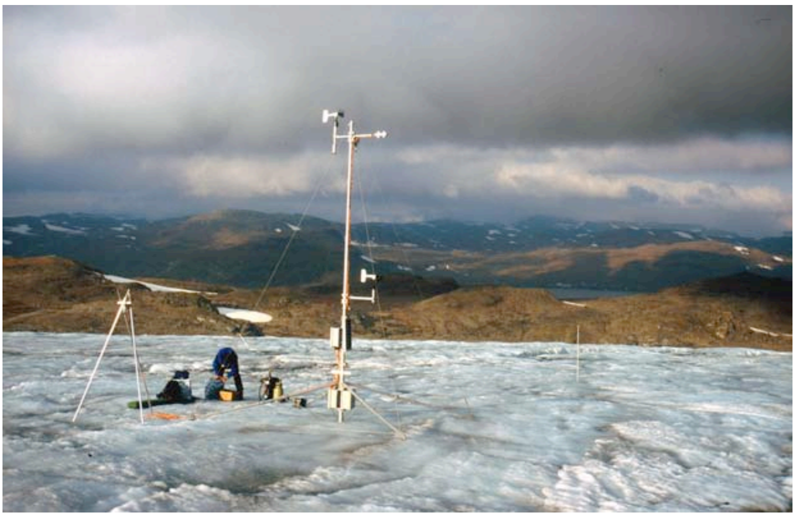
**Figure 2:** The IMAU-AWS on Hardangerjökulen, Norway, in September 2000 (photo by Wim Boot). The mast has four legs and stands freely on the ice. The mast is about 6 m high. Two sonic rangers are used: one on a tripod drilled in the ice (8 m stakes), and one in the mast (below the Young anemometer).

At present (March 2004) eight automatic weather stations are in operation in ablation zones (Figure 1/ Table 1): three in Central-west Greenland along the Kangerlussuaq mass-balance transect (Greuell et al, 2001); one on Breidamerkurjökull, Iceland; two on the Morteratschgletscher, Switzerland; two in southern Norway (Hardangerjökulen, Figure 2; Storbreen). Most of these stations have records extending over many years. Morteratsch-I has a record since October 1995 without any significant gaps.

The toughest conditions are encountered on Breidamerkurjökull, Iceland. High ice velocities and associated crevassing, large melt rates (10 m of ice in a summer), high wind speeds, and salt from sea spray make the operation of AWS difficult. Relatively favourable climatic conditions are experienced in West Greenland, where the climate is dry and sunny with a small snow accumulation rate. However, here the surface topography is very rough.

The data sets from the weather stations have been used to study the microclimate of a melting glacier surface. We have found that in all ablation zones shallow katabatic flows are very persistent and in a way regulate the turbulent exchange of heat and momentum. By selecting sites with a very different climatic setting we have revealed very different partitions of the melt energy over the various energy sources. As an illustration of differences in climate we show in Figure 3 daily mean values of global radiation a sites in West Greenland, Breidamerkurjökull and Morteratschgletscher. The difference between Breidamerkurjökull and West Greenland is particularly large, in spite of the fact that the AWS are located at roughly the same latitude. In this case the effect of differences in cloudiness is overwhelming.

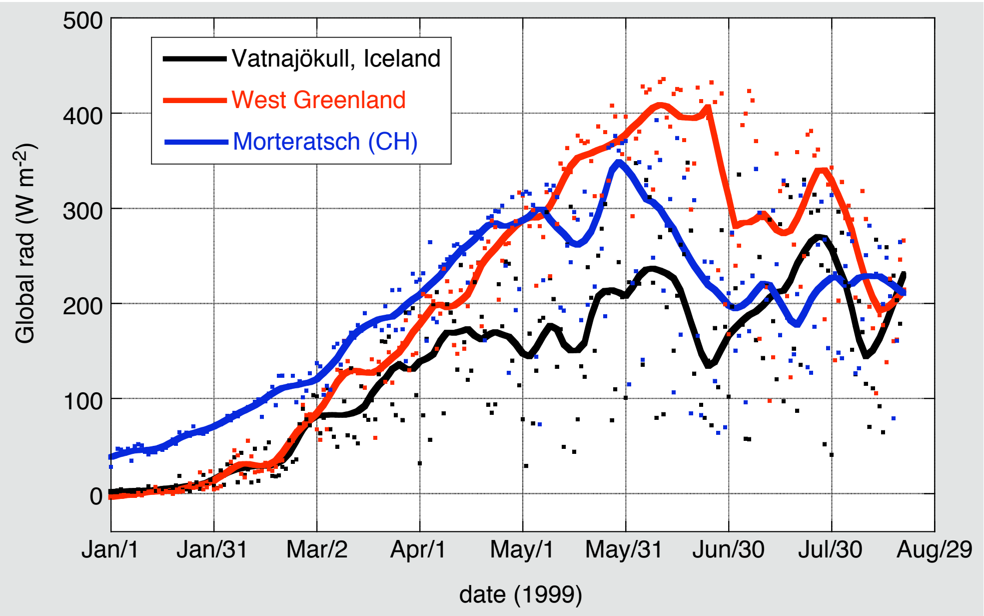


**Figure 3:** Daily mean values of global radiation at three different AWS sites. In the ablation zone of the ice sheet in West Greenland global radiation is about twice as large as on Breidamerkurjökull, Iceland.

The AWS data have been used extensively to construct parameterizations for energy balance models (e.g. De Ruyter de Wildt et al., 2003; Klok and Oerlemans, 2002). This involves for instance the relation between cloudiness and radiation, and schemes to relate the surface albedo to the thickness and the age of the snowpack.

Our AWS have been changed significantly in the course of time. We have tried to find the best instruments for typical conditions in melting zones. Young anemometers appeared to be more robust with respect to icing. We also think that the Kipp CNR-1, measuring all 4 components of the radiation budget, is a surprisingly good instrument. The use of sonic rangers turned out to be very useful. First of all it is instructive to have a picture of the cumulative balance with very high resolution. In addition, the possibility to detect snow events is of great value when the data from the radiation instruments are interpreted (and the other way around: we have observed many times that the albedo is well above 1, presumably because the upward facing sensor is covered with snow and the downward facing sensor is not; this can the be checked with the sonic ranger).

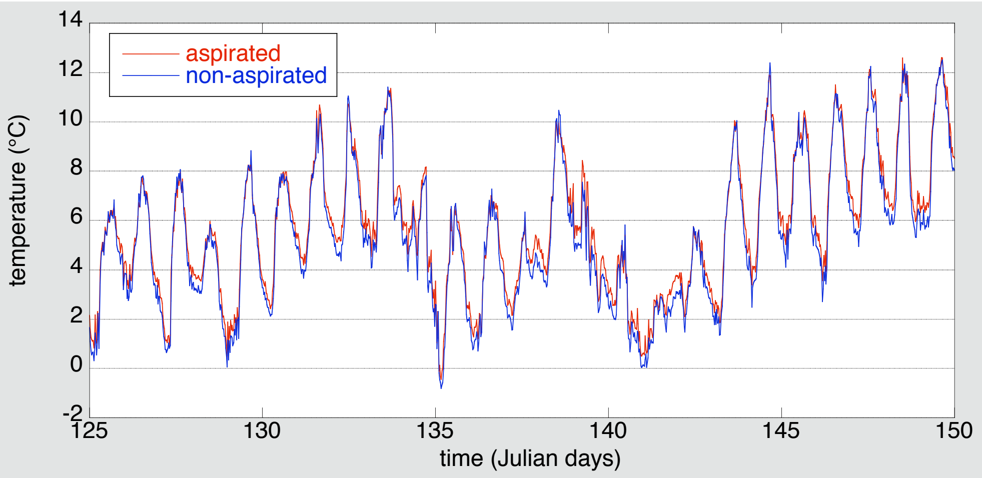


**Figure 4:** A comparison of temperature measurements (30-min values) with an aspirated and a non-aspirated instrument. The sensors were placed on different masts a few m apart. Height of the instruments: about 3.5 m.

Aspiration of sensors is a difficult point, especially when at high latitudes no solar energy is availble during the winter months. Aspirating radiation sensors is without reach, but for most AWS we have introduced a low-capacity aspirator for the temperature/humidity sensor. At the Morteratschgletscher (lower station) two AWS have been operated parallel for over a year. This has provided a good opportunity to compare instruments. Just as an example Figure 4 shows a comparison between an aspirated (Vaisala HMP35AC, with forced ventilation) and a non-aspirated temperature sensor (Aanderaa 2775C) for a period in spring, when radiation errors are expected to be largest.

The collection of data continues, and we plan to extend and improve the data sets. The data sets will mainly be used to (1) study the relation between microclimate of the glacier surface and the climatic conditions in the surrounding terrain, (ii) calibrate and validate energy balance models and more general atmospheric models, (iii) validate quantities derived from satellite imagery, notably albedo.

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# MEASURING HUMIDITY AT TEMPERATURES WELL BELOW ZERO

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## Introduction: History of IMAU AWS

The Institute for Marine and Atmospheric Research Utrecht (IMAU) first started meteorological measurements on glaciers in 1986 with a short-term (10 days) experiment on the Hintereisferner in Austria. The meteorological stations that were used consisted of a mast drilled into the ice and fixed by guy wires to the ice. The disadvantage of this setup was that melting of the glacier surface made it necessary to adjust the wires almost every day. The desire to keep the sensors at a fixed level above the melting surface and the desire to operate the stations for long time periods without the need to service resulted in the development of an automatic weather station (AWS, type 1) that rests freely on the surface (Figure 1, left frame). These AWS were equipped with Aanderaa sensors for temperature, wind speed, wind direction, incoming solar radiation and sonic altimeter. The station was placed on four legs and the sensors were not ventilated for reasons of energy efficiency (Figure 1). The first year-round station was placed in the ablation area of the Greenland ice margin east of Kangerlussuaq in 1990.

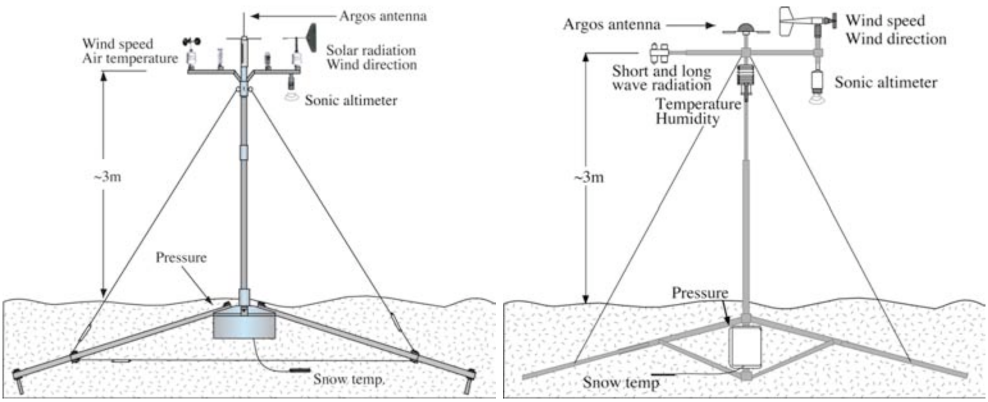


**Figure 1:** Schematic figures of the first 2 types of weather stations deployed by the IMAU.

In 1997, a new AWS (type 2, figure 1 right frame) was developed to solve several problems encountered with AWS type 1. The temperature and humidity sensors are still not ventilated or heated. A few examples of the changes made are given here.

- The logger box of AWS type 1 was an integral part of the construction, attaching the four legs to the mast and containing the electronics as well as the batteries. This made data retrieval and battery replacement a difficult task. In AWS type 2 the electronics and batteries are in two separate boxes for easier access.

- The Aanderaa temperature sensors turned out to be very sensitive to radiation errors because of the small housing and the black underside of the radiation shield. The sensors were replaced by Vaisala temperature and humidity sensors in a bigger radiation shield, adding humidity to the measured parameters.
- The cup anemometer and wind vane were replaced by a Young wind sensor. Experience shows that the Young sensor is less prone to freezing, owing to its black color and faster response to changes in wind speed.
- The incoming shortwave radiation sensor is replaced by a Kipp CNR1 sensor, which measures the full radiation balance.

The addition of the humidity sensor and radiative fluxes makes it possible to more accurately calculate the surface energy fluxes from the AWS (see Van den Broeke *et al.,* this volume).

In 2000 a type 3 AWS was developed for areas where high accumulation resulted in burial of the sensors. The station height was increased and an extra measurement level was added.

We also encountered problems caused by the harsh environment in which we measure. For example, on glaciers, where the stations experience ablation in summer and accumulation in winter, melt water in the logger box, connectors and instruments occasionally cause problems. On Antarctica, temperatures well below the specifications of the instruments result in problems with data transmission and the necessity of extra corrections to the data, for example to the humidity measurements. An example of how relative humidity measurements are corrected for temperatures well below freezing is given below.

## Correction of relative humidity measurements

This method was presented first by Anderson (1994) and also applied to Greenland AWS by Box (2001). Our AWS are equipped with the Vaisala HMP35AC relative humidity (*RH*) sensor. The HMP35AC is based on the Vaisala humicap sensor, which is a capacitive device calibrated in the factory to measure *RH* with respect to water ($RH_w$) within a specified temperature (*T*) range (–20°C to +56°C). The fact that it measures *RH* with respect to water leads to unrealistic behavior for temperatures below 0°C namely a clear decrease in upper limit *RH* <100% with decreasing temperature (Figure 2a). To remedy this, $RH_w$ is recalculated to *RH* with respect to ice ($RH_i$) for $T < 0$°C. To obtain $RH_i$ from $RH_w$, $RH_w$ is multiplied by the ratio of saturated vapor pressures over water ($e_{s,w}$) and ice ($e_{s,i}$):

$$RH_i = RH_w \frac{e_{s,w}}{e_{s,i}}$$

To calculate $e_s$ from temperature *T* the expression of Curry and Webster (1999) is used:

$$e_s = e_0 \exp\left[\frac{1}{R_v}\left(L + T_0\beta\right)\left(\frac{1}{T_0} - \frac{1}{T}\right) - \left(\beta \ln\left(\frac{T}{T_0}\right)\right)\right],$$

where $T_0$ and $e_0$ are the temperature and water vapor pressure at freezing point of water (273.16 K and 6.1078 hPa, respectively). Furthermore, $R_v$ is the gas constant for water vapor (461.51 J K$^{-1}$ kg$^{-1}$), $\beta$ is a constant equal to 2317 J K$^{-1}$ kg$^{-1}$

and L is the latent heat of either vaporization or sublimation ($2.501 \times 10^6$ J kg$^{-1}$ and $2.83 \times 10^6$ J kg$^{-1}$, respectively). The result is that *RH* values are substantially increased (Figure 2b).

This step is enough to obtain reasonable values for *RH* for most of our AWS, because they are located in areas where winter temperatures do not drop regularly

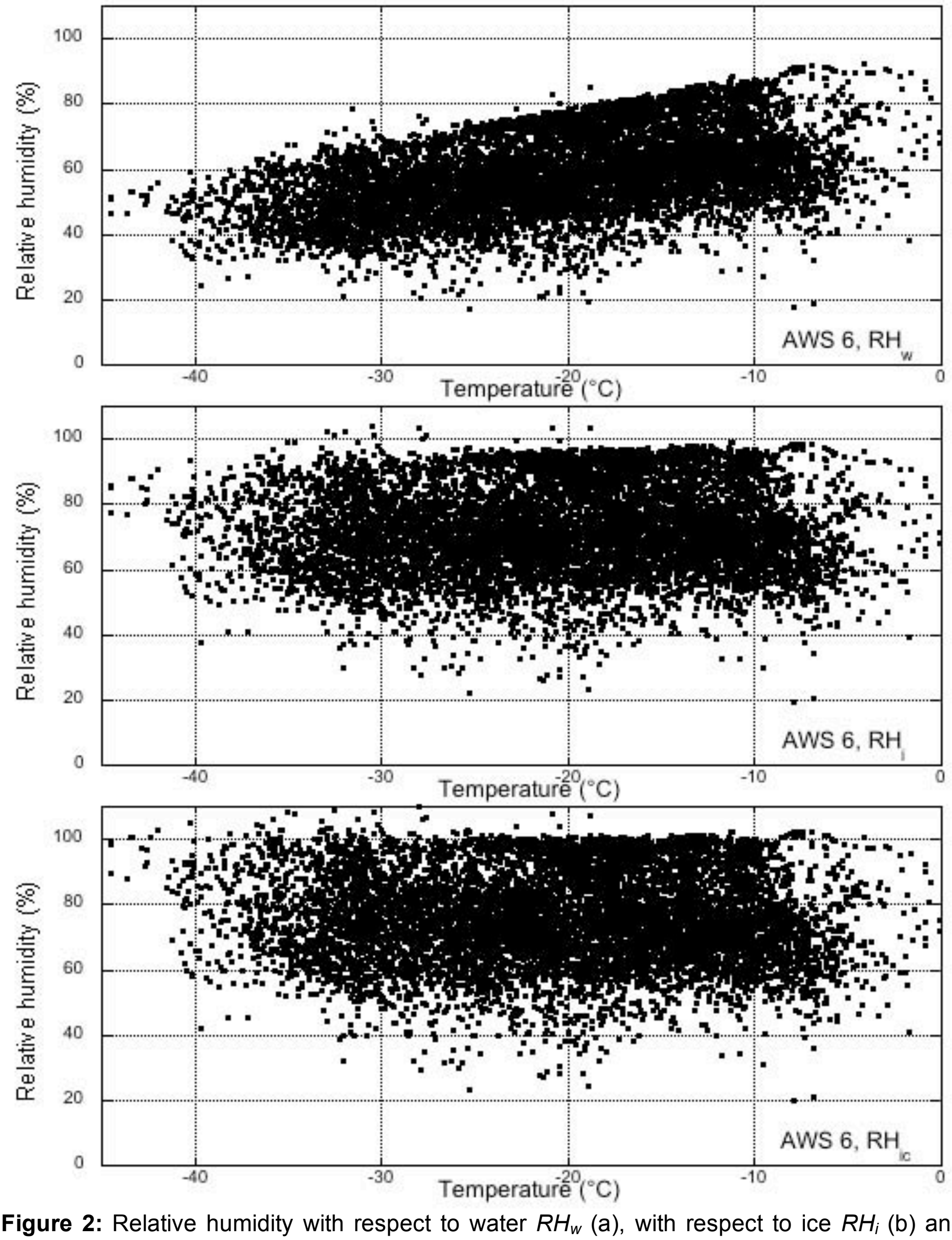


**Figure 2:** Relative humidity with respect to water $RH_w$ (a), with respect to ice $RH_i$ (b) and rescaled $RH_{ic}$ (c) as a function of temperature measured at an AWS site in Dronning Maud Land, Antarctica (1160 m a.s.l.), 1998-2000 (Van den Broeke et al, 2004).

below –20°C. However, our Antarctic stations all experience temperatures below –20°C for large parts of the year. Figure 2b shows that there still is an artificial upper limit of measured *RH* with decreasing temperature, especially below about –20°C. The specifications of the instrument ensures accurate output within a temperature range of –20°C to +56°C (at 20°C: 2%, *RH* < 90% and 3%, *RH* > 90%). To achieve this, a quadratic fit is incorporated in the instrument. Anderson (1994) mentions that, to extend this temperature range to –60°C to +180°C, a sixth order polynomial is required. This sixth order polynomial replaces the quadratic fit, and must be applied to the raw, uncorrected data. Therefore, one needs the exact quadratic correction already applied on the instrument to recalculate the raw instrument output and then reapply the sixth order polynomial. Since the correction already applied and the sixth order polynomial are often not available, Anderson (1994) proposes an alternative method to extend the accuracy range of the data based on the partially corrected output.

The first step in this correction is to bin all $RH_i$ values in 1 K intervals. Then a second order polynomial function is fitted to the 98$^{th}$ percentile. Using the 98$^{th}$ percentile allows for 2% occasional spuriously high values. It does not allow for supersaturation to be measured; the design of the sensor does not allow for supersaturation (Makkonen, 1996). The final step is to use the fit to correct the data upwards to 100% $RH_i$ . This is done by way of rescaling.

$$RH_{ic} = \frac{RH_i}{fit}$$

Here, $RH_{ic}$ is the rescaled relative humidity with respect to ice and *fit* is the second order polynomial function. The correction is based on rescaling because, according to Anderson (1994), the upper limit error in the measurements is very likely in the gain of the instrument rather than being an offset. Figure 2c presents the results for one of the Antarctic AWS. Note that the correction is sensor dependent.

This way of correcting the data seems to work well for our Antarctic weather stations. However, recent studies question the reliability of the humicap sensor in cold environments. Dery and Steiglitz (2002) compare measurements of the Vaisala HMP35AC with a dew-cell hygrometer and saw that the HMP35AC has a strong tendency to measure saturated values. This is probably due to icing of the sensor housing. In general, solid objects act as nucleation sites for moisture. For $T < 0$°C, this results in a porous ice coating on the sensor. The air that diffuses through the coating and reaches the sensor, will therefore be saturated with respect to ice and the probe will be at 100% $RH_i$. Icing of the housing occurs also at our measuring sites on Antarctica (Figure 3) especially on the coastal ice shelves and on the plateau. We therefore may expect that the *RH* readings are not always reliable. On the other hand, at our Antarctic AWS significant undersaturation is observed throughout the year. Comparison experiments at the sites two Antarctic AWS sites in summer show excellent agreement between ventilated and unventilated temperature and humidity measurements. Furthermore, Anderson (1996) shows that rescaled $RH_i$ measurements from a Vaisala HMP35A are reassuringly good down to –40°C when compared with a frost-point hygrometer. This method therefore seems a good option to extend the temperature range in which the Vaisala sensors give acceptable results.

**Figure 3:** The Vaisala HMP35AC temperature and humidity sensor in a 10-plate Gill radiation screen at an AWS site in Dronning Maud Land, Antarctica (2892 m a.s.l.,)(photo H. Oerter, AWI Bremerhaven).

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# CORRECTION OF AIR TEMPERATURE DATA MEASURED BY NATURALLY VENTILATED SENSORS OVER SNOW AND ICE

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## Abstract

Air temperature data were acquired using different measurement systems as part of a field campaign in the Kärkevagge, Sweden, during snowmelt in 1998. A comparison reveals that temperatures from naturally ventilated sensors exceed those from aspirated sensors by as much as 6.2 K. Even higher errors have been reported by a number of authors. The errors are closely connected to high values of upwelling short-wave radiation, and are larger in periods of low wind speed. All data were stored as minutely means. Errors result from instantaneous radiation conditions, but propagate over the next measurements due to slow response time of the naturally ventilated sensor.

A physically based model was developed for the correction of air temperature data susceptible to radiation errors. The model computes air temperature errors based on additional data on wind speed and upwelling short-wave radiation. The latter is generally higher over snow and ice surfaces compared to other surface types showing lower albedo values. The parameters of the model, which are treated as effective ones although having a physical meaning, are automatically determined from the erroneous temperature measurements themselves by inverse modelling. Therefore, the correction method does not depend on concurrent accurate air temperature measurements.

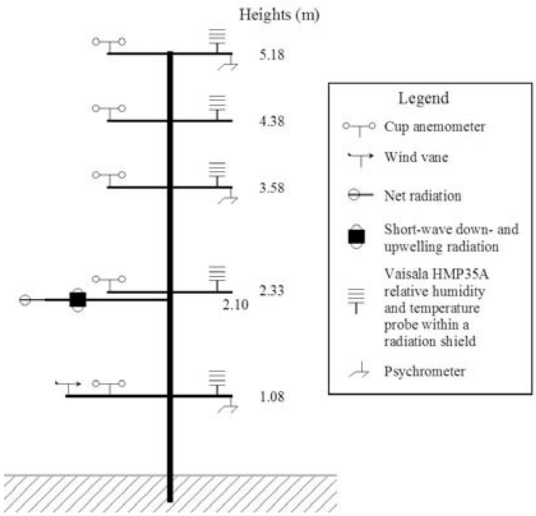


**Figure 1:** Instrumentation used during the field campaign in the Kärkevagge, Swedish Lapland, during the snowmelt season in 1998.

The high quality of the correction method could be validated by the highly accurate psychrometer measurements. One of the most important applications is the computation of sensible heat fluxes from snow-covered surfaces during the snowmelt period using the bulk-aerodynamic method, which is greatly improved by the new correction method. In addition, the correction could be applied to many existing data sets, since it is physically based but does not make any assumptions on the details of the measurement configuration (sensor, shields, heights, etc.). The authors look forward to further validate the method by using comparable data sets from other research groups.

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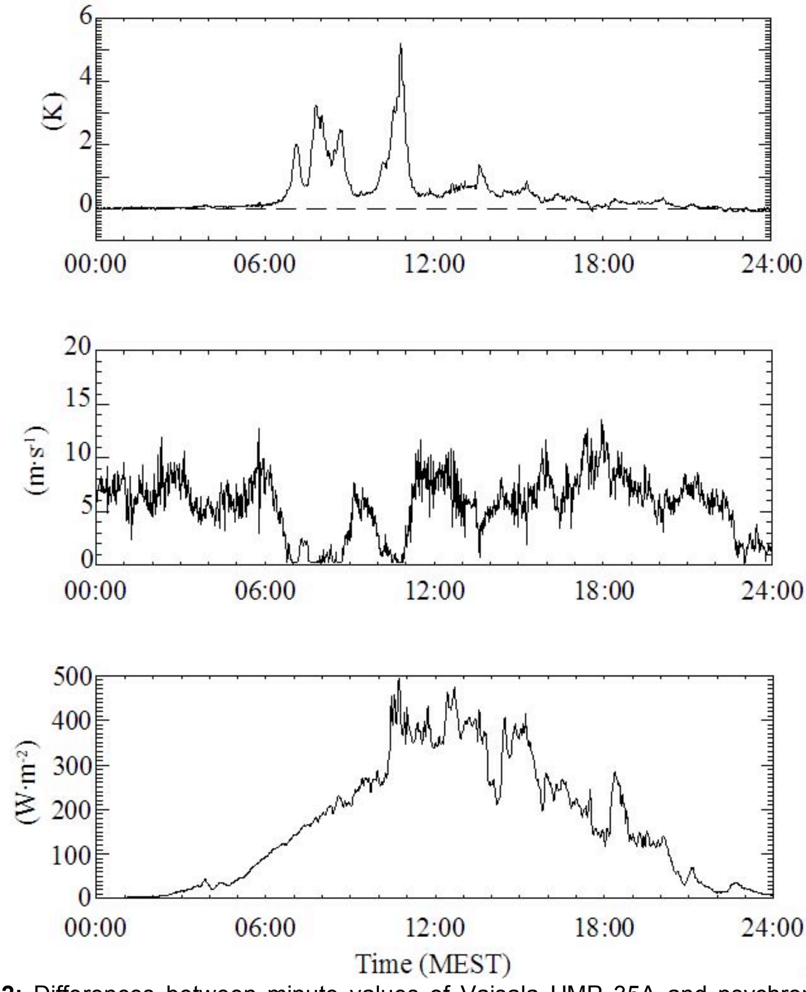


**Figure 2:** Differences between minute values of Vaisala HMP 35A and psychrometer air temperatures (upper graph), and their dependencies on wind speed (middle graph) and upwelling short-wave radiation (lower graph), measured on May 30, 1998.

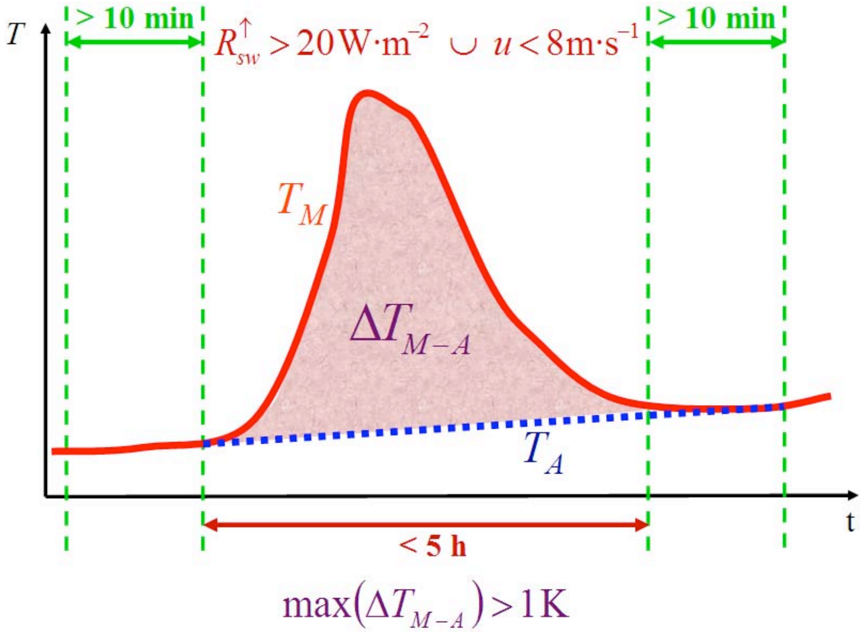


**Figure 3:** Automatic error detection used for extracting those measurements from the erroneous temperature time series that are a) susceptible to radiation errors, and b) for which the 'true' temperature values can be well approximated by linearly interpolating between the adjacent, undisturbed measurements. Detected errors, i.e., the differences between measured and interpolated air temperatures, are used for determination of the correction parameters by inverse modelling.

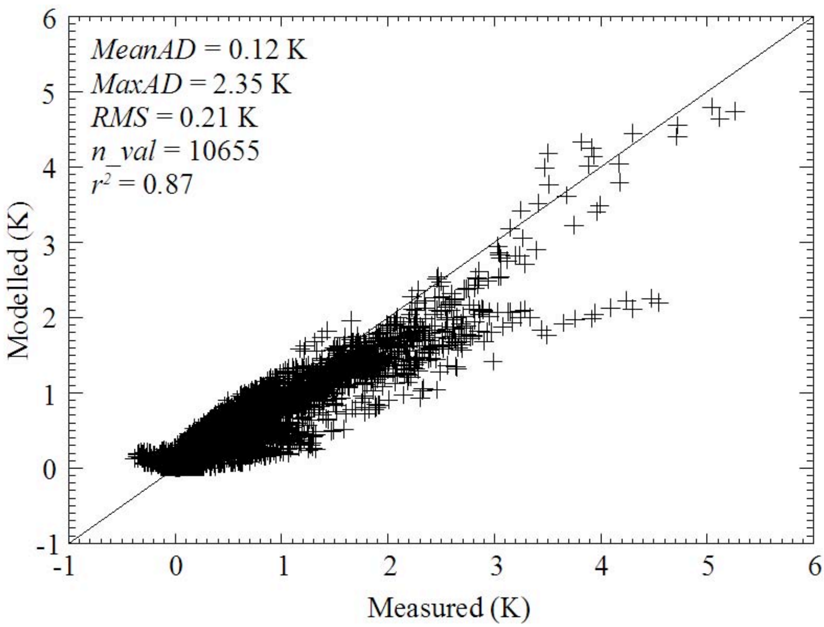


**Figure 4:** Comparison of modelled and measured temperature differences for the whole measurement period.

# ASPECTS OF LOGISTICS AND POWER CONSUMPTION FOR THE OPERATION OF AWS IN HARSH ENVIRONMENT IN SOUTHERN PATAGONIA

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## Motivation, study area and climate conditions

Since October 1999 the Gran Campo Nevado (GCN) Project Group operates a set of automatic weather stations (AWS) along a profile from west to east through the Patagonian Andes at 53°S. This profile is completed by two standard weather station of the Navy of Chile at Faro Evangelistas (52°24'S/75°06'W at sea level) and of the Instituto de la Patagonia at Punta Arenas (53°08'S/70°53'W, 6 m asl) (Figure 1). While three AWSs at Paso Galería (52°45'S/73°01'W, 383 m asl), Puerto Bahamondes (52°48'S/72°56'W, 26 m asl) and Estancia Skyring (52°33'S/71°58'W, 8 m asl) are permanently run, an additional AWS was maintained on Glaciar Lengua, an outlet glacier of the GCN ice cap, from February 2000 until April 2000 at 450 m asl. This study is the first that addresses glacier changes and regional climate pattern of this part of the Andes.

The main goals are:

- to reveal the meso-scale pattern of climate, especially precipitation rates
- to investigate weather pattern along the profile related to synoptic circulation types
- to document glacier changes during recent decades and
- to find out how these changes may relate to climate variability.

The study area is located in the west wind zone of the southern hemisphere. Therefore, the area is affected by high mean wind speed from the west and almost permanent advection of moist and moderately cool air from the Pacific Ocean. In consequence, climate is very windy and maritime. There are extreme gradients of precipitation between about 3,000 mm of annual precipitation at the west coast, more than 6,000 mm at sea level in the Cordillera and less than 500 mm in the east at Punta Arenas (Schneider et al. 2003). Daily and annual cycles of air temperature are very moderate due to the oceanic climate setting with a mean air temperature of 5.7°C at sea level at the GCN Ice Cap. At 53°S the Cordillera of the Andes consists of single mountain ridges separated into islands and peninsulas by channels and fjords. Summits reach altitudes mostly between 1000 m and 1800 m asl. The GCN Ice Cap is located on the southern part of Península Muñoz Gamero. It covers a surface area of 200 km$^2$ (Figure 1). From a summit plateau at approximately 1,500 m asl outlet glaciers reach down to altitudes between sea level and about 200 m asl. Aerial photography and satellite images show that the ice cap has lost about 16% of its surface area since 1942 (Schneider et al. 2004a).

## Logistic constraints

The area under investigation is accessible only by ship since it is completely uninhabited. The next helicopter base is located at Punta Arenas about 100 km from the GCN Ice Cap. Frequently occurring bad weather conditions with heavy wind and low hanging clouds and quickly changing weather conditions further hinder operations by helicopter. The GCN Project Group owns a small 13 m long research motor ship which allows to navigate the narrow channels of the area. Access to the glacier is given by a three to four hour walk through pathless dense rain forest and bog. Therefore, all of the necessary equipment on the glacier must be carried by foot.

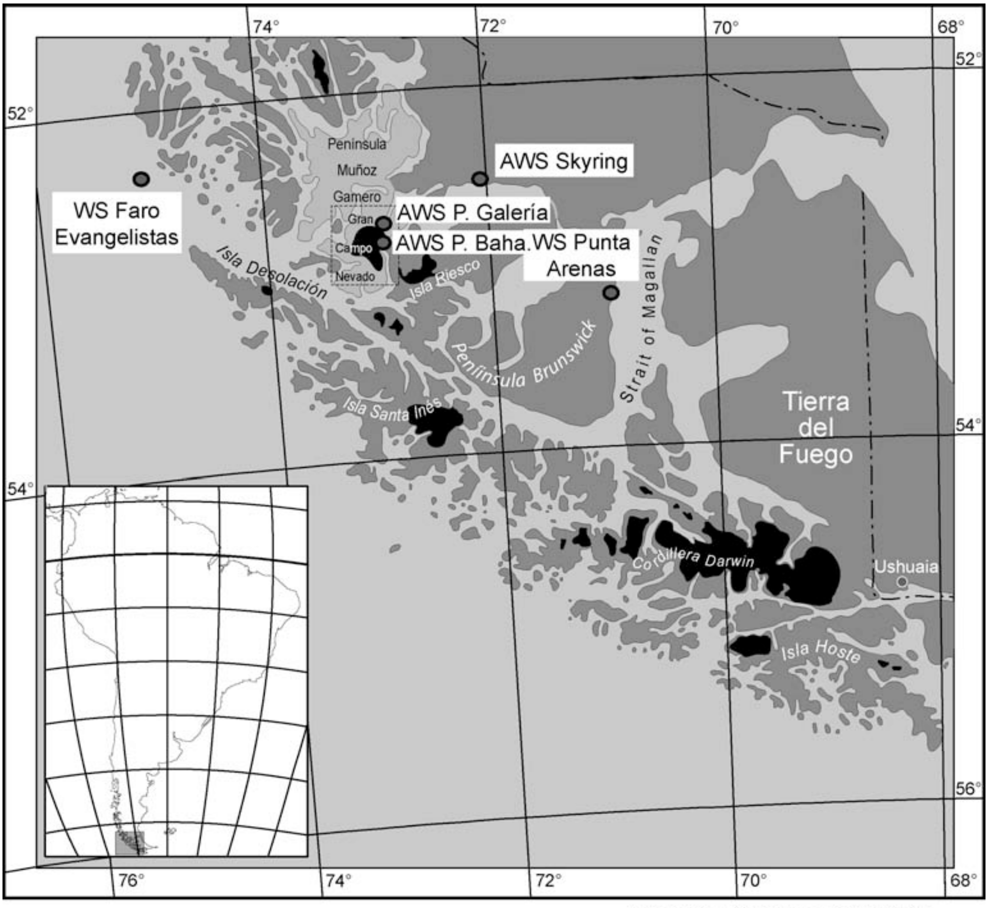


**Figure 1:** Location of some WS and the AWS of Gran Campo Nevado Project in the Southwest of Patagonia, black: glaciated areas.

## Set-up of AWS and measurements

The AWS use a Campbell Scientific “21X” data logger which operates standard devices for the measurement of air temperature and air humidity at two levels, wind speed and wind direction, short-wave irradiance and short-wave reflected radiation, radiation balance, fluid precipitation and ice temperature at two levels (Figure 2). In order to facilitate the transportation of the AWS the standard tripod of Campbell Sci. was replaced by a light-weighted alloy construction.

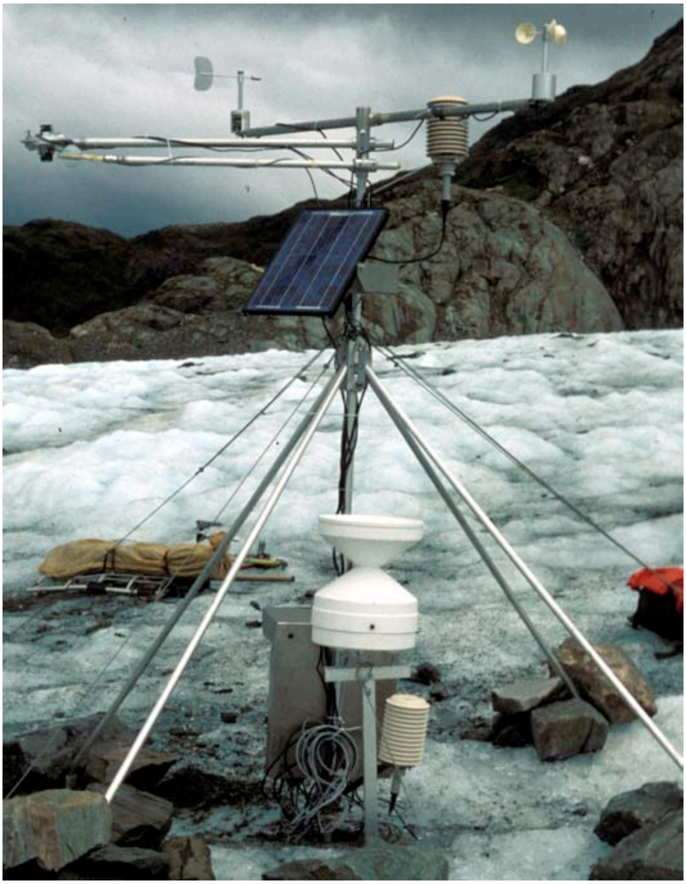

**Figure 2:** AWS on Glacier Lengua at 450 m asl.

A party of four people was able to transport the AWS by foot to the ablation area of the glacier even through crevassed areas. However, instrumentation and fixation of the AWS on the ice had to be kept to a minimum. This kind of basic AWS is suitable to record standard meteorological conditions and can be used to calculate energy balance with the bulk method during time periods with melting at the glacier surface (Schneider et al. 2004b). Radiation shields of temperature probes must be kept unventilated due to the limited power supply by a 10 W solar panel. This is only of minor importance since mean wind speed was above 4 m/s and time periods with light winds occur only rarely. Furthermore, the effect of heating of the temperature probe through radiation can be corrected based on short-wave incoming radiation and wind speed during time periods with little wind speed (Schneider 1998).

While the AWS on Glacier Lengua was only operated for 9 weeks to investigate the energy balance during the summer season on Glacier Lengua the other AWS in the area were supposed to work year-round. During the first winter it became clear that the standard Campbell Sci. set-up with a 10 W solar panel was not able to sufficiently recharge the internal battery of the "21X" logger which resulted in the shut down of the AWS at Puerto Bahamondes in late June. Therefore, the charging electronics of the data logger were replaced by a unit that charges the internal battery either from the solar panel during time periods with strong solar radiation or during night time and during bad weather periods by an external 12 V battery pack using 8 standard batteries of 1.5 V each. It is calculated that the external battery pack by itself would be able to supply the AWS with energy for a period of about 50 days before the breakdown of the system. The adapted AWS at Puerto Bahamondes operates until the present day without any further loss of data.

AWS Puerto Bahamondes allows to calculate the ablation on Glaciar Lengua using a degree day model fitted to the specific circumstances of the glacier. Using regression analysis between monthly mean data from AWS Puerto Bahamondes and air temperature data from Punta Arenas and precipitation data from WS Faro Evangelistas and NCEP/NCAR data it is even possible to estimate the glacier mass balance during the last decades.

At Paso Galería further loss of data resulted from two failures of the cable between the solar panel and the data logger. The cable broke because it became lose and was rubbed through during stormy winds and the plug of the cable at the entrance to the logger was corroded after two winter seasons and had to be replaced. Unfortunately each failure resulted in the subsequent destruction of the internal battery of the logger by total discharge. However, since the data are stored in a self-powered storage module ("SM 192") data loss is limited to the time periods after the breakdown of the system.

## Conclusion

Standard AWS can be adapted to suit the logistic constraints of remote areas. Although these AWS are not equipped with high-end precision instruments, the data are very valuable since they may be the only data ever acquired in some glaciated regions as is the case at the GCN Ice Cap. It was possible to operate an AWS close to the glacier for several years with intervals between maintenance of up to 8 months near the GCN. This allows to relate measured ablation to climate variables on a time span of several years. However, it is still a challenging task to address the spatial and temporal variability of precipitation in the area and the accumulation rates on the summit plateau of the GCN Ice Cap.

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# Greenland Climate network (GC-Net)

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The GC-Net was established in spring 1995 with the intention of monitoring climatological and glaciological parameters at various locations on the ice sheet over a time period of at least 10 to 15 years. The first AWS was installed in 1990 at the Swiss Camp, followed by four AWS in 1995, four in 1996, five in 1997, four in 1999, and two in 2000. Our objectives for the Greenland weather station (AWS) network are to measure daily, annual and inter-annual variability in accumulation rate, surface climatology and surface energy balance at selected locations on the ice sheet, and to measure near-surface snow density at the AWS locations for the assessment of snow densification, accumulation, and metamorphosis.

The GC-Net currently consists of 20 stations (Table 1) with a distributed coverage over the Greenland ice sheet. Four stations are located along the crest of the ice sheet (2500 to 3200 m elevation range) in a north-south direction, ten stations are located close to the 2000 m contour line (1830 m to 2500 m), and four stations are positioned in the ablation region (560 m to 1150 m).

**Table 1:** Greenland Climate Network (GC-Net) Automatic Weather Stations (AWS).

| Station | Station Name | Latitude and Longitude | Altitude (m) | Activation |
|---|---|---|---|---|
| 01 | Swiss Camp | 69° 34' 06" N, 49° 18' 57" W | 1149 | 1990.30 |
| 02 | Crawford Pt. 1 | 69° 52' 47" N, 46° 59' 12" W | 2022 | 1995.39 |
| 03 | NASA-U | 73° 50' 31" N, 49° 29' 54" W | 2369 | 1995.41 |
| 04 | GITS | 77° 08' 16" N, 61° 02' 28" W | 1887 | 1995.43 |
| 05 | Humboldt | 78° 31' 36" N, 56° 49' 50" W | 1995 | 1995.47 |
| 06 | Summit | 72° 34' 47" N, 38° 30' 16" W | 3208 | 1996.37 |
| 07 | Tunu-N | 78° 01' 0" N, 33° 59' 38" W | 2113 | 1996.38 |
| 08 | DYE-2 | 66° 28' 48" N, 46° 16' 44" W | 2165 | 1996.40 |
| 09 | JAR 1 | 69° 29' 54" N, 49° 40' 54" W | 962 | 1996.47 |
| 10 | Saddle | 66° 00' 02" N, 44° 30' 05" W | 2559 | 1997.30 |
| 11 | South Dome | 63° 08' 56" N, 44° 49' 00" W | 2922 | 1997.31 |
| 12 | NASA-E | 75° 00' 00" N, 29° 59' 59" W | 2631 | 1997.34 |
| 13 | Crawford Pt. 2 | 69° 54' 48" N, 46° 51' 17" W | 1990 | 1997.36* |
| 14 | NGRIP | 75° 05' 59"N, 42° 19' 57" W | 2950 | 1997.52 |
| 15 | NASA-SE | 66° 28' 52" N, 42° 19' 20" W | 2360 | 1998.30 |
| 16 | KAR | 69° 41' 58" N, 33° 00' 21" W | 2579 | 1999.38 |
| 17 | JAR 2 | 69º 25' 12" N, 50º 03' 27" W | 568 | 1999.41 |
| 18 | KULU | 65° 45' 30" N, 39° 36' 06" W | 878 | 1999.46* |
| 19 | JAR3 | 69º 23' 42" N, 50º 18' 35" W | 323 | 2000.41 |
| 20 | Aurora | 67º 08' 06" N, 47º 17' 28" W | 1798 | 2000.48* |
| 21 | Petermann Gl. | 80º 40' 32" N, 60º 15' 19" W | 32 | 2002.43 |
| 22 | Petermann ELA | 80º 05' 02" N, 58º 04' 02" W | 965 | 2003.45 |

* Station discontinued

## Instrumentation

Each AWS is equipped with a number of meteorological and glaciological instruments (Figure 1) to measure the following parameters: (a) the surface height change at high temporal resolution to identify and resolve individual storms; (b) the radiation balance at the surface; (c) temperature, humidity and wind speed profiles in the surface boundary layer; (d) the snow pack conductive heat flux that also describes the energy dissipation from refreezing of percolated melt water. Additional meteorological parameters such as wind direction, pressure, and short-wave incoming and reflected radiation are also recorded.

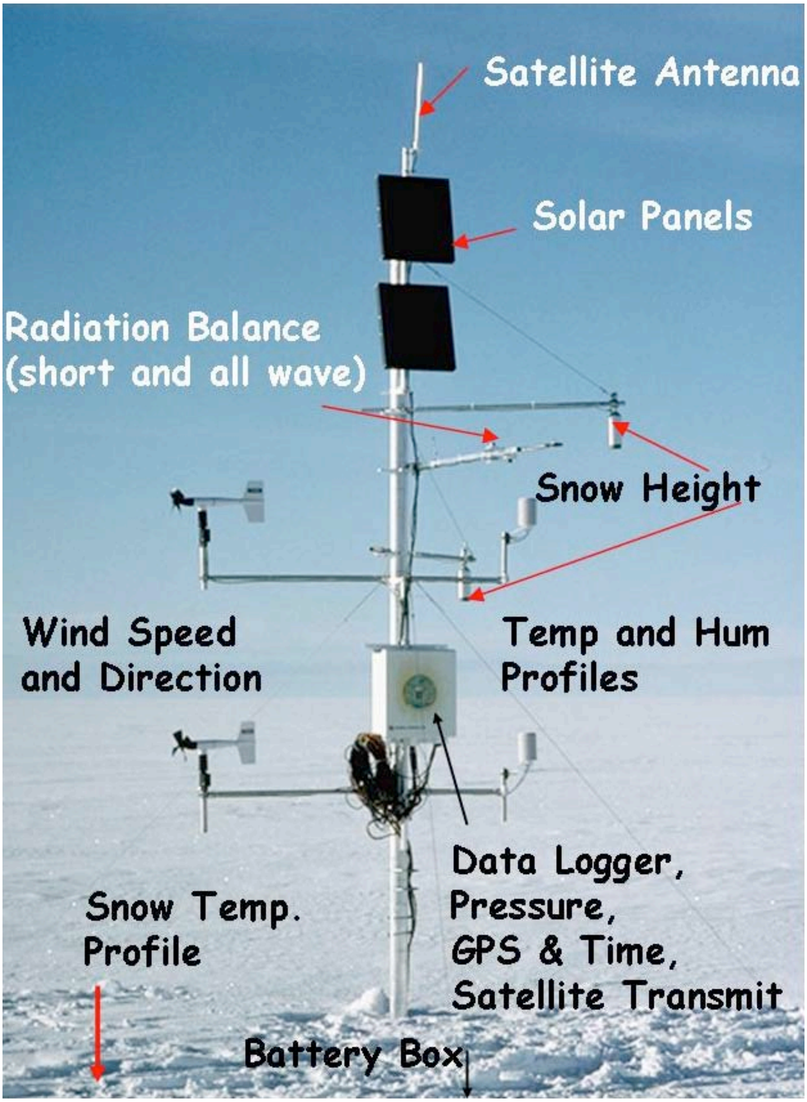


**Figure 1:** GC-Net automatic weather station instruments.

The shortwave and net radiation fluxes are sampled at 15 s intervals and averaged over 60 minutes. Snow temperatures (10 sensors at 1 m spacing) are sampled every 15 s and averaged every hour. Air temperature, relative humidity, and wind direction are sampled every 60 s and averaged over 60 minutes. The sampling rate for air temperature and wind speed was set at 15 s at the 1999 site visit. Snow heights are sampled every 10 min and pressure and battery voltage once in the hourly interval. The datalogger clock is updated once a day using a Global Position System (GPS) receiver to eliminate clock drift. A total of 32 parameters are transmitted hourly via a satellite link (GOES for stations location south of 72° N, and ARGOS for the stations north of 72° N). In addition, all the measurements are stored on-site in solid-state memory that can hold 36 months worth of continuous measurements for up to ten years. The data logger is powered from two 100 Ah batteries which are charged with a 20 W solar panel. The satellite link is powered separately with an identical power reserve. This design helps guarantee continuous data recordings, even in the case of transmitter failure.

## Calibration

GC-Net instruments come factory calibrated. Nonetheless, on-site relative temperature, humidity and wind speed calibrations are performed to ensure relative accuracy of gradient measurements. The deviation from one sensor to the other is adjusted to zero using a multiplier representing the inverse of the percent mean deviation during a calibration of 7 to 24 hours. Some of the AWS do not have relative calibration coefficients due to inclement weather and time constraints. Field calibrations are set for at least one half of an entire diurnal cycle in attempt to represent the relative bias between the profile instruments over a range of local conditions. The resultant corrections are typically less than 3%. Relative accuracy of profile instruments is greater than the absolute accuracy stated by the instrument's manufacturer.

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# HOW USEFUL ARE SURFACE RADIATION BALANCE OBSERVATIONS FROM AUTOMATIC WEATHER STATIONS IN ANTARCTICA?

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## Introduction

The surface radiation balance can be written as:

$$R_{net} = SHW_{net} + LW_{net} = SHW\downarrow + SHW\uparrow + LW\downarrow + LW\uparrow, \quad (1)$$

where fluxes towards the surface are defined positive, $R_{net}$ is net radiation and SHW↓, SHW↑, LW↓, LW↑ are the downwelling and upwelling fluxes of shortwave and longwave radiation. At present, only three stations in Antarctica accurately measure the surface radiation balance as part of the Baseline Surface Radiation Network (BSRN) (Ohmura *et al*., 1998): Neumayer, Syowa and South Pole (Figure. 1). To fill in the resulting observational gaps, Automatic Weather Stations (AWS) may prove valuable. In 1997/98, an array of AWS was installed in western Dronning Maud Land, Antarctica, equipped with unventilated /unheated radiation sensors that measure the four surface radiation balance components. Van den Broeke *et al*. (2004) discuss in detail the quality of radiation data of three of these AWS, and this paper summarizes the main results.

## Data and instrumentation

We use data of three AWS situated on the coastal ice shelf (AWS 4), in the katabatic wind zone (AWS 6) and on the polar plateau (AWS 9) (Figure 1). A picture of AWS 9 is given in Figure 2a with the radiation sensor enlarged in Figure 2b. The katabatic wind climate at AWS 5 and 6 is characterized by low relative humidity, high wind speed and high (surface) potential temperature (Bromwich, 1989; Van den Broeke *et al*., 1999), which prevents riming of the radiation sensors (Van den Broeke *et al*., 2004). At AWS 4 and 9 the surface is nearly flat; here, wind speed and potential temperatures are lower and relative humidity higher, and riming occurs frequently.

The AWS are equipped with Kipp & Zonen (K&Z) CNR1 net radiometers (Figure 2b). The K&Z CNR1 houses two K&Z CM3 pyranometers for downward and upward broadband shortwave radiation flux (spectral range 305-2800 nm, ISO 9060 second class specifications i.e. estimated accuracy for daily totals +/- 10%) and two K&Z CG3 pyrgeometers for downward and upward broadband longwave radiation flux (spectral range 5 to 50 µm, factory-provided estimated accuracy for daily totals +/- 10%). A heating element is included in the sensor housing to prevent dew/rime deposition; however, this heating option is not used as this would deplete AWS batteries too rapidly. Until 2002, out of a possible 1200 radiation-component-months (5 AWS x 5 years x 12 months x 4 components), 88 radiation-component-months (7.3%) were lost of which 82 (6.8%) at a single station, AWS 8. Apart from the sensor malfunctioning at AWS 8, for which no obvious explanation is available, the K&Z CNR1 appears to be a reliable instrument for unattended use in the harsh climate of Antarctica.

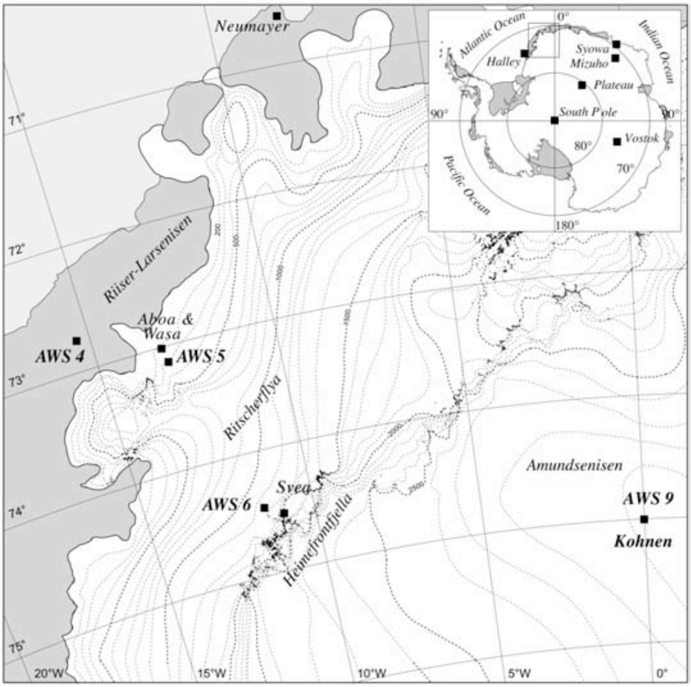


**Figure 1:** Map of western Dronning Maud Land, Antarctica, with AWS and station locations, main topographical features, ice shelves (grey) and height contours (dashed lines, every 100 m).

## Results: summer

The accuracy of the AWS radiation measurements was assessed in summertime comparison experiments at Neumayer in February 2002 (Van den Broeke *et al*., 2002), near AWS 6 in January/February 1998 (Bintanja, 2000) and at Kohnen base in January/February 2002 (Van As *et al*., 2004). During these experiments, the AWS sensors were directly compared to instruments of a higher standard, namely the K&Z CM11 for shortwave and the Eppley PIR for longwave radiation. Only at Neumayer were the reference sensors heated and ventilated.

The experiments show that Root Mean Square Differences (RMSD) for individual fluxes are smaller than 5 % for daily averages, so the K&Z CM3 and CG3 perform better than their specifications. With a RMSD of about 1%, LW↓ shows especially good agreement at Neumayer (where the Eppley PIR is ventilated); a larger and systematic difference is found when the K&Z CG3 is compared to the unventilated Eppley PIRs. Comparison with (extrapolated) snow temperatures suggest that the problem may be partly due to the Eppley PIR measurements, a problem that will be investigated further. The comparison experiment performed at Kohnen further revealed that the single domed K&Z CM3 is much less sensitive to riming than is the double domed K&Z CM11.

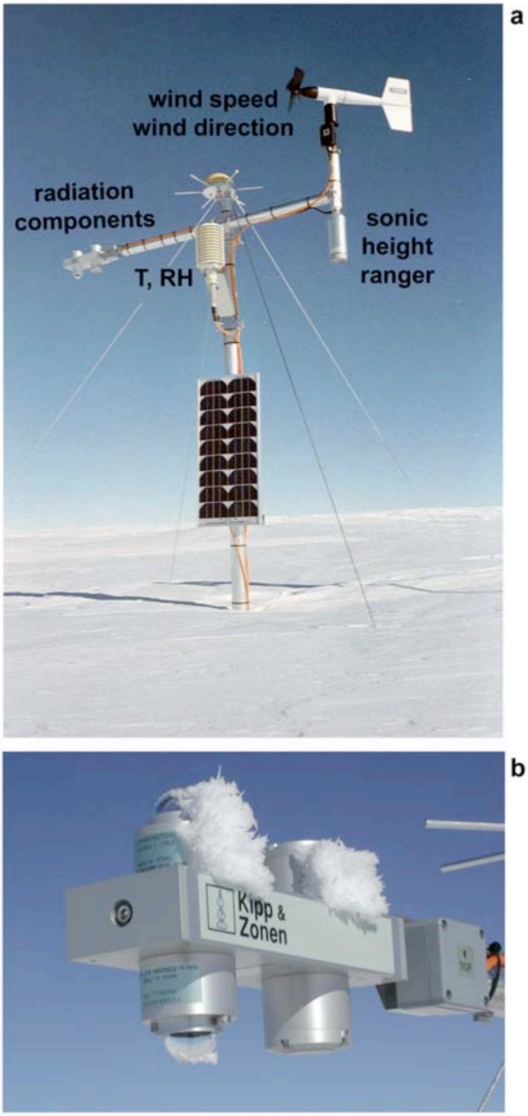


**Figure 2:** a) picture of AWS 9. The data logger and pressure sensor are buried in the snow; b) enlarged image of K&Z CNR1 radiation sensor.

In spite of the good accuracy of the single components, $SHW_{net}$, when calculated from individual pairs of SHW↑ and SHW↓, has very large RMSD for 2 h averages, up to 30%. Two factors are responsible: a) the upward directed pyranometer that faces the direct solar beam is much more sensitive to measurement errors associated with a poor cosine response and sensor tilt than is the downward facing sensor, which receives radiation that is largely isotropic and b) when the surface albedo is high, $SHW_{net}$ is the difference between two large values, resulting in potentially large relative errors. Figure 3a highlights this problem for a sunny 3-day period at Svea Cross (28-30 January 1998). The top-of-atmosphere (TOA) incoming radiation, scaled and offset for reference, is also included. Large amplitude and phase differences occur between the K&Z CM3 and CM11. Owing to a relatively poor cosine response, the K&Z CM3 even produces negative night time values of $SHW_{net}$. However, neither the K&Z CM3 nor the CM11 is in phase with TOA, which suggests that phasing errors occur in both.

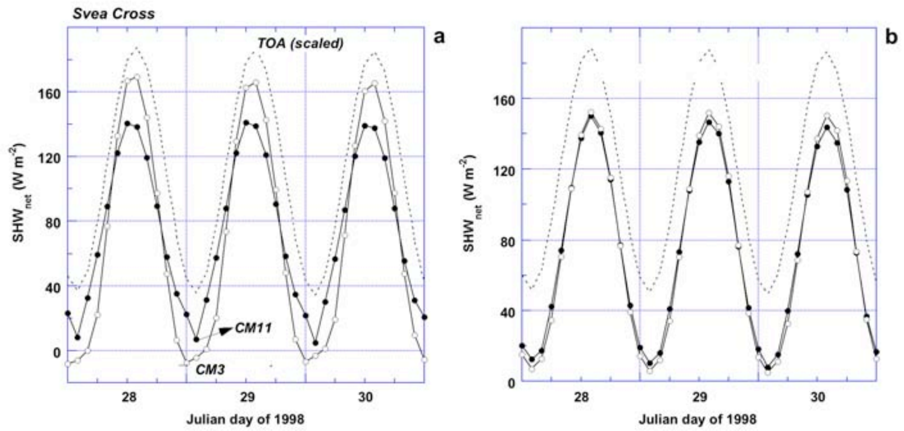


**Figure 3:** a) SHWnet for three days of fair weather at Svea Cross, as measured with the Kipp and Zonen (K&Z) CM3 and K&Z CM11. SHW↓ at top-of-atmosphere (TOA) is also shown, scaled and offset for comparison; b) same as above, but after correction using the method of 'accumulated albedo'.

The error in $SHW_{net}$ can be reduced by choosing SHW↑ as the basis for the calculation of $SHW_{net}$:

$$SHW_{net} = -SHW\uparrow(1+\alpha)/\alpha \cong -SHW\uparrow(1+\alpha_{acc})/\alpha_{acc}$$

$$\alpha_{acc} = \sum_{24h} |SHW\uparrow| / \sum_{24h} SHW\downarrow \qquad (2)$$

Here, $\square_{acc}$ is an 'accumulated' albedo, i.e. the ratio of accumulated |SHW↑| and SHW↓ over a time window of 24 h centred around the moment of observation. The underlying idea of this approach is that albedo changes due to snow metamorphism are likely to be small on sub-daily time scales, while the use of $\square_{acc}$ largely eliminates errors in SHW↓ that are associated with a poor cosine response and phase shifts due to a possible tilt. Figure 3b shows that applying (2) greatly improves amplitude and phase of the measurements. An obvious disadvantage of the 'accumulated albedo' method is that we have eliminated the clear sky daily cycle in □. This deficiency may be remedied by adding a theoretical daily cycle □□ $\square_{acc}$, for which the theoretical albedo model for a pure, semi-infinite snowpack by Wiscombe and Warren (1980) can be used.

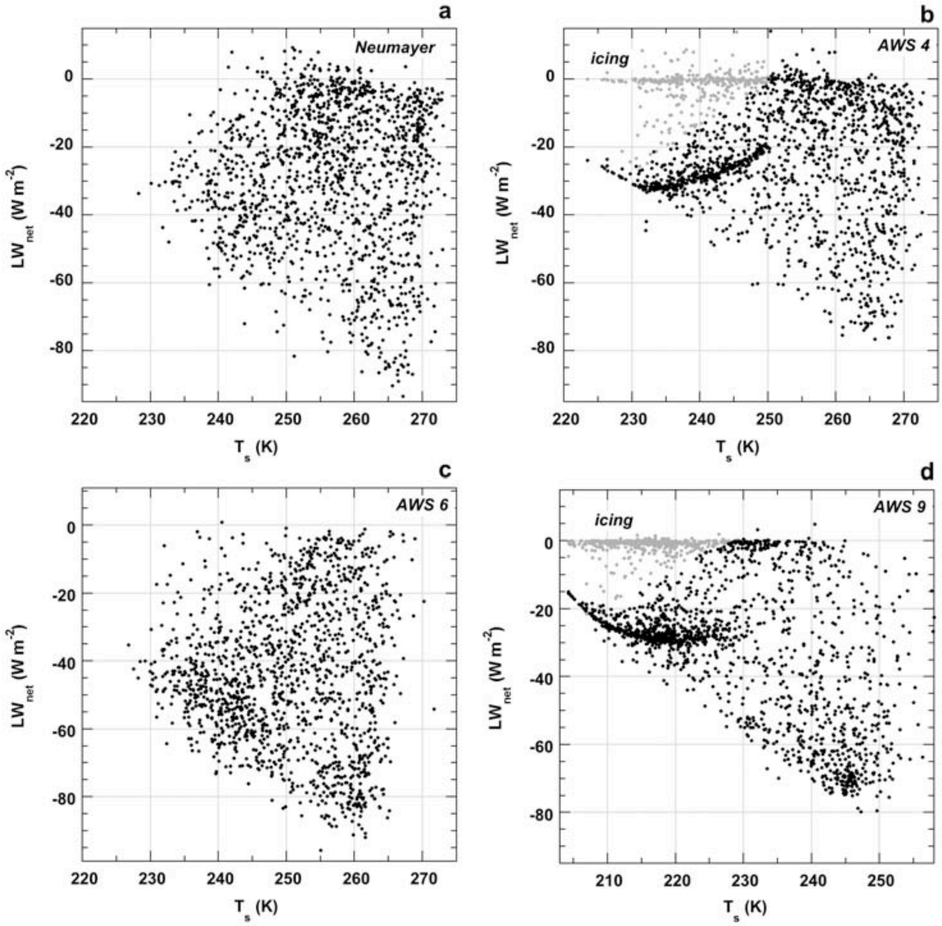


**Figure 4:** Daily means of incoming (LW↓, dots) and absolute value of upwelling (LW↑, upper line) longwave radiative flux as a function of surface temperature $T_s$ at (a) Neumayer, (b) AWS 4, (c) AWS 6 and (d) AWS 9. For AWS 4 and 9, the rejected data are in light grey. The fitted lower boundary for the parameterization of LW↓ (lower line) is included.

## Results: winter

Due to energy considerations, the K&Z CNR1 at the AWS are unventilated and unheated. On the ice shelf (AWS 4) and on the high plateau (AWS 9), this leads to frequent wintertime riming of both the upward and downward looking CG 3. Since riming completely obstructs the passage of longwave radiation, both LW sensor signals (a measure for the temperature difference between sensor surface and the object it looks at) approach zero and $LW_{net} = 0$. The problem becomes evident if we plot $LW_{net}$ as a function temperature. At AWS 4 and 9, the combination of $LW_{net} = 0$ and low T is frequently found (grey dots). This implies riming, because low T *must* be associated with significantly negative $LW_{net}$, as this is the only significant surface heat sink in winter. This is supported by the measurements at Neumayer, and AWS 6, where sensors remained free of rime. Wintertime riming at AWS 4 and 9 leads to 25 and 29% LW data rejection, respectively. The problem can be partly solved by using a parameterization for LW↓ as a function of T. A full surface energy balance calculation along the lines of Reijmer and Oerlemans (2002) can be used to calculate surface temperature and hence LW↑. The result is that no longer $LW_{net}$ = 0 is found at low temperatures (Figures 4b and d); note, however, that the parameterized /calculated $LW_{net}$ values at AWS 4 and 9 cluster more than the measured values at AWS 6 and Neumayer.

## Conclusions

If properly analysed and corrected, reliable radiation observations can be made at unmanned platforms in Antarctica using the relatively low-cost and robust Kipp and Zonen CNR1 net radiometer. The greatest problem is wintertime riming of the longwave sensor windows at the AWS situated on the ice shelf and the high plateau. Future efforts should focus on preventing this, for instance through forced ventilation and/or heating using a separate power supply in combination with a wind generator.

## Acknowledgments

We wish to thank the IMAU technical department for AWS development and support. Participants of SWEDARP'97/98 are thanked for setting up AWS 4, 5 and 6 and hosting the Svea experiment. Personnel of the Alfred Wegener Institute is thanked for the setting up and maintenance of AWS 9 as well as hosting the Kohnen experiment. Use of the Neumayer radiation data is also gratefully acknowledged. Field parties of IMAU are thanked for maintenance work on AWS 4, 5 and 6. This work is partly funded by the Netherlands Antarctic Program (NAAP) and the Netherlands Organisation of Scientific Research, section Earth and Life Sciences (NWO/ALW).

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# CALCULATING AND VALIDATING THE SURFACE ENERGY BALANCE IN THE KATABATIC WIND ZONE OF ANTARCTICA, USING SINGLE-LEVEL AWS DATA

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## Introduction

The surface energy balance (SEB) can be described as

$$M = SHW\downarrow + SHW\uparrow + LW\downarrow + LW\uparrow + SHF + LHF + G_s \quad (1)$$

where M is melting energy (M = 0 if surface temperature $T_s$ < 273.15 K), SHW↓ and SHW↑ are incoming and reflected shortwave radiation fluxes, LW↓ and LW↑ are incoming and emitted longwave radiation fluxes, SHF and LHF are the turbulent fluxes of sensible and latent heat and $G_s$ is the surface value of the conductive heat flux into the snow, G. All terms are defined positive when directed towards the surface. Measured and/or calculated values of the Antarctic SEB are sparse, and automatic weather stations (AWS) may help remedy this. Van den Broeke *et al.* (2004a) describe in detail how the SEB in Antarctica can be calculated from single-level measurements from Antarctic AWS; this paper summarizes the main results.

## Instruments and methods

We use four years (1998-2001) of AWS 6 data. This AWS is situated in the katabatic wind zone of western Dronning Maud Land (see Figures. 1 and 2 in Van den Broeke *et al.*, elsewhere in this volume). Katabatic winds prevent the formation of rime on the radiation instruments (Van den Broeke *et al.*, 2004b) and assure a sufficient natural ventilation of the thermometer/relative humidity sensor housing, thus keeping radiation errors to a minimum. Moreover, eddy-correlation measurements are available for this site to compare the calculated SHF and LHF with (Bintanja, 2000).

Basic parameters like air pressure, wind speed and direction, temperature and relative humidity are measured at a single level app. 3 m above the ground at the date of AWS installation. The changing sensor height is monitored with a sonic height ranger. Downward and upward shortwave and longwave radiation fluxes are measured with a Kipp and Zonen CNR1. Snow temperatures are measured at 5 levels at initial depths of 0.05, 0.1, 0.2, 0.4 and 0.8 m.

Net shortwave radiation is obtained using the method of 'accumulated albedo' (Van den Broeke *et al.*, 2004b). Calculating SHF and LHF from single level atmospheric measurements requires the use of the 'bulk' method, which uses measurements of wind speed, temperature and specific humidity at one atmospheric level as well as surface values. This makes it much less sensitive to instrumental error than the 'profile' method, in which two levels in the atmosphere are used (Stearns and Weidner, 1993; Box and Steffen, 2001). On the other hand, it requires knowledge of Ts and surface roughness for momentum. The latter is acquired from on-site eddy correlation measurements performed in a 1997/98 experiment (Van den Broeke, 2004c); its value of 0.16 mm is assumed constant in time. The surface roughness lengths for temperature and moisture are calculated from the formulation of Andreas (1987). For the sub-surface heat flux G we use a snow model with 4 cm thick snow layers down to 20 m; Gs is obtained by upward extrapolation of the values at 2 and 6 cm depth. Snow thermal conductivity is a function of snow density and shortwave penetration in the snowpack is neglected.

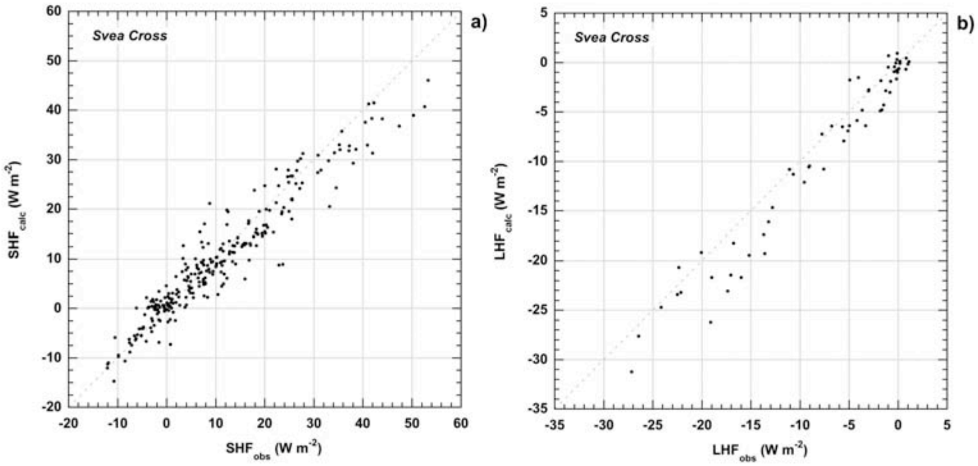


**Figure 1:** Comparison of calculated and measured SHF (a) and LHF (b) at AWS 6 (situated at 'Svea Cross') for a summer period in January 1998.

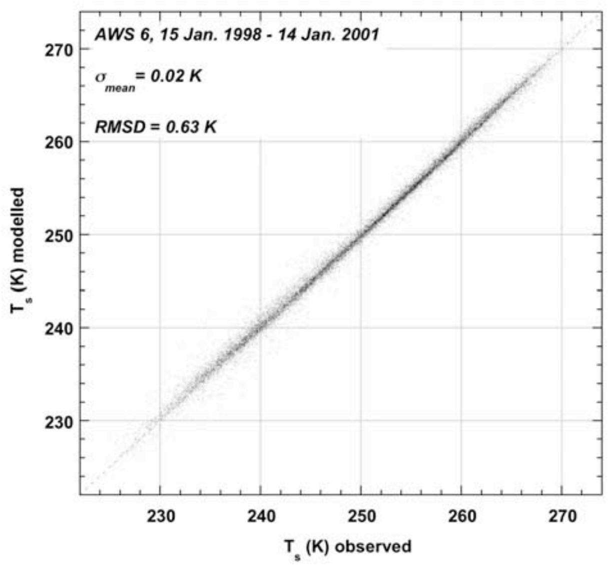


**Figure 2:** Scatterplot of 'measured' (derived from LW↑) and modelled surface temperature $T_s$, based on two-hourly averages for a four-year period.

$T_s$, finally, can be either obtained from LW↑ (assuming the snow to have unit longwave emissivity and using Stefan Boltzmann's law), or by solving the full energy balance equation (1) for $T_s$ using a fast search routine. This requires iterative loops, as SHF and LHF depend on the vertical profiles, for which we use the profile functions of Holtslag and De Bruin (1988).

## Results

Figure 1 compares LHF and SHF calculated using the bulk method (with $T_s$ derived from LW↑) with directly measured values. Agreement is quite good with RMSD of 2.4 and 4.1 W $m^{-2}$ for LHF and SHF, respectively.

'Measured' and modelled $T_s$ have a Root Mean Squared Difference (RMSD) of only 0.6 K. The correspondence is so close that short periods of large differences can be used as a flag for sensor malfunctioning. An example is given in Figure 2, which shows the two-week period surrounding 20 October 1999, the only occasion on which the wind speed sensor froze at AWS 6. As a result, modelled SHF and LHF become zero (Figure 3b) and modelled $T_s$ becomes much too low (Figure 3a). As soon as the wind speed sensor starts functioning again, the difference quickly vanishes.

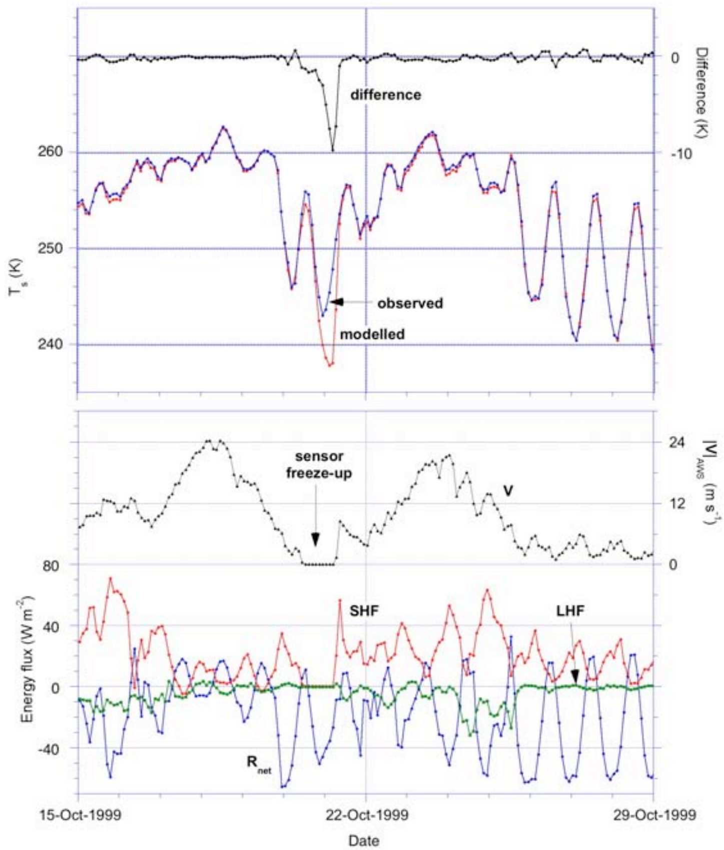


**Figure 3:** a) Modelled and measured surface temperature $T_s$ and b) net radiation $R_{net}$, SHF and LHF at AWS 6 for a two week period surrounding a windspeed sensor freezing event.

A test of the modelled $G_s$ is how well sub-surface snow temperatures are simulated. Figure 4 shows modelled (with $T_s$ derived from LW↑) and measured snow temperatures for sensor 3 which was situated at 0.2 m depth upon the date of installation in January 1998, and became progressively deeper buried in the snow. Upon reaching a depth of nearly 2 m, the sensors was replaced at 0.2 m again in January 2000. Over this depth range and a temperature range of 25 K, differences between simulated and measured snow temperature are typically smaller than 1 - 2 K.

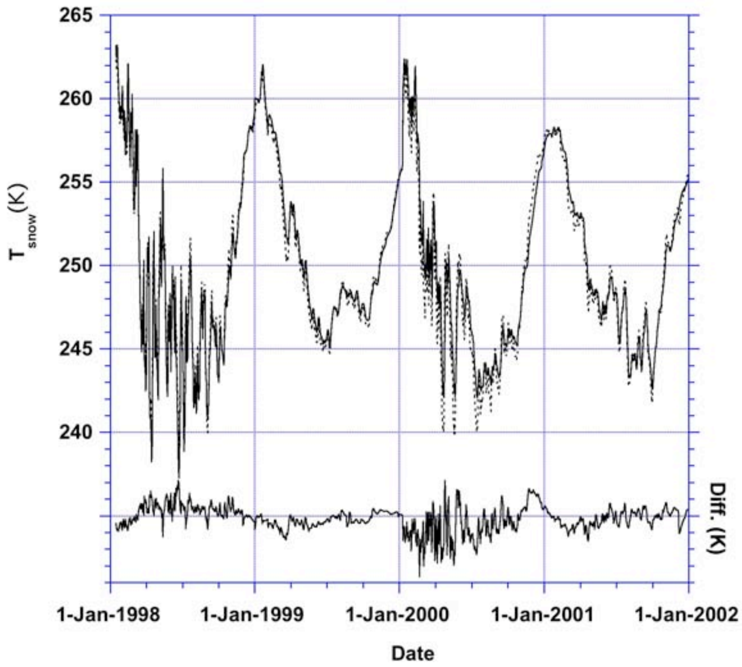


**Figure 4:** Measured and modelled snow temperature (upper lines) and the difference (lower line). Depths of snow temperature sensors ranges from 0.2 to 2 m.

## Conclusions

On the condition that reliable measurements of the radiation components are available as well as a snow density profile, sub-surface snow temperatures and a good estimate of the surface roughness for momentum, single level AWS measurements are suitable for accurate determination of the Antarctic surface energy balance. In this paper we demonstrated this for a site in the katabatic wind zone where, admittedly, problems associated with riming are usually small.


## Acknowledgments

We wish to thank the IMAU technical department for AWS development and support. Participants of SWEDARP'97/98 are thanked for setting up AWS 6 and hosting the Svea experiment. Field parties of IMAU are thanked for maintenance work on AWS 6. This work is partly funded by the Netherlands Antarctic Program (NAAP) and the Netherlands Organisation of Scientific Research, section Earth and Life Sciences (NWO/ALW).

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# PORTABLE AWS RUNNING IN REMOTE HIGH AREAS IN THE TROPICAL ANDES OF BOLIVIA, PERU, ECUADOR

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Since 1996, a meteorological-glaciological program has been undertaken on tropical glaciers located in Bolivia, Peru and Ecuador by the French research institute IRD (Institut de Recherche pour le Développement). The aim of this program is to better understand the relationship between climate and glacier under low latitudes. To reach this goal, monthly mass balance measurements together with long-term surface energy balance investigations are conducted on different locations of the ablation area of various glaciers. Moreover, ice cores are collected in very high altitude sites in order to give insight into low-latitude past climates.

Therefore, several AWS have been running in the ablation area of Zongo Glacier (Bolivia, 16°S, 5050 m asl, and 5150 m asl) [Wagnon *et al.,* 1999, 2001] and in the ablation area of Antizana Glacier (Ecuador, 0°28'S, 4900 m asl) [*Favier et al.,* Submitted] in order to get the annual cycle of the surface energy balance (SEB) of these tropical glaciers. A similar program will start in 2004 on Artesonraju (Peru, 9°S, 5050 m asl). On very high altitude drilling sites (Illimani, Bolivia, 17°S, 6340 m asl and Coropuna, Peru, 14°S, 6090 m asl), we also try to make AWS running in order to calculate the SEB and to study post-depositional processes due to sublimation [Wagnon *et al.,* 2003].

In the Andes, we have to face several problems to run AWS on glaciers. More specifically, AWS must be light and portable because helicopters cannot be available at very high altitude. Although light, AWS must be strong because of high wind speed (up to 30 m $s^{-1}$ above 6000 m asl). Especially in Ecuador but also at very high altitude in Bolivia and Peru, riming can be a very serious problem. In my presentation, I will focus on the specific problems we have to face under these tropical high altitude climates.

Therefore, simple devices of AWS have been designed. An example of such a station is presented in the Figure. This AWS is a free standing station made of an aluminum tripod and a 2.5 m aluminum mast. Sensors are 1 thermo-hygrometer Vaisala HMP45C at 1m (air temperature and humidity), 1 05103 Young anemometer at 2.5 m (wind velocity and direction), 2 Kipp&Zonen CM3 pyranometers (incident and reflected solar radiation), 2 Kipp&Zonen CG3 pyrgeometers (incoming and outgoning long-wave radiation). The data logger is a Campbell CR10X supplied by a dry 12V battery charged by a solar panel. A second solar panel provides energy for the Vaisala artificial ventilation. The weight of the AWS is less than 30 kg.

Thanks to this simple AWS, it is possible to get the SEB: radiative fluxes are measured directly and the turbulent fluxes are derived with the bulk aerodynamic approach using direct sublimation measurements to calibrate the surface roughness lengths. When the surface in not in melting conditions (at very high altitude sites), additional vertical profiles of snow temperature are measured in the first 50 cm below the surface using 6 Cu-Cst thermocouples and a Campbell CR10 data logger. The reference temperature is done by an ice-water bath.

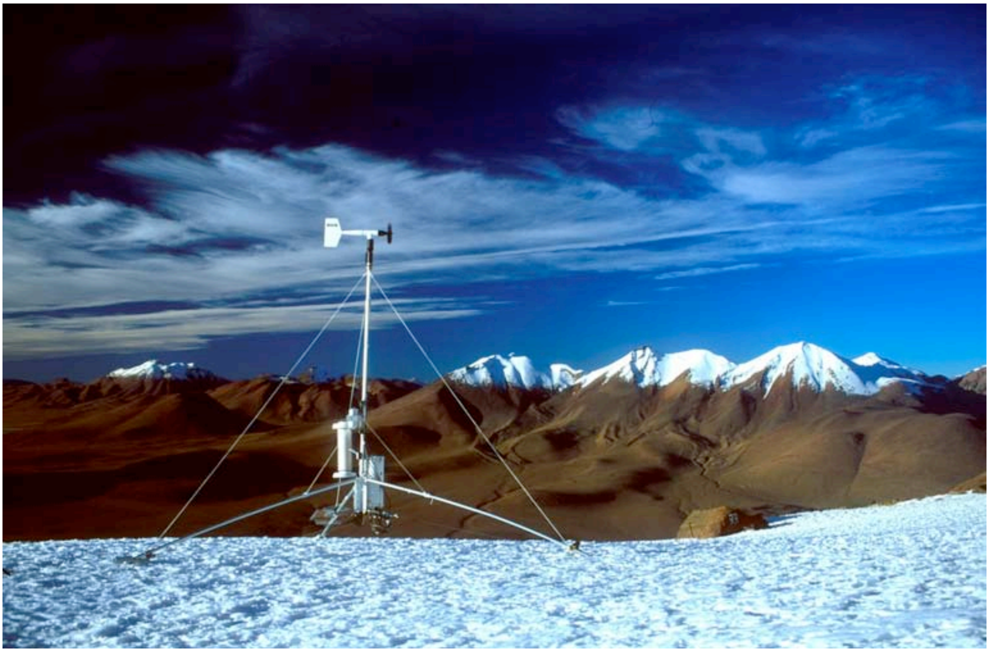

**Figure:** AWS used in Bolivia, Caquella rock glacier (5350 m asl). Photo P. Wagnon, April 2001.

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