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Scientific note

***In-situ* snow temperature monitoring at an Arctic tundra site: A comparison of manual and automatic measurements**

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Abstract: The physical properties of snow in the Arctic play an important role for the surface energy balance and Arctic biota. By measuring snow temperatures, the physical condition of the snowpack can be monitored. Conventionally, snow scientists measure snow temperature vs. depth in snow pits. An alternative to those destructive and time-consuming measurements is automated temperature logging using permanently installed sensors. At an Arctic research site on Svalbard we did both, manual and automatic snow temperature measurements. The measurements were performed before and after the onset of melt in May and June 1998, when various snow properties change quickly. Our results show that in the lower part of the snowpack, both datasets deviate usually not more than ± 0.2°C. In the upper part of the snow pack, measurements are often distorted by solar radiation, especially after the onset of melt, once the snow is more transparent due to metamorphosis. When measuring in snow pits, shadowing the surface can reduce this effect. A substantial advantage of the automatic measurements is the better temporal resolution and the non-destructiveness. On the other hand, from manual snow-pit measurements, multi-parameter datasets in combination with sampling on regional scales can be collected.

1. Introduction

1.1. Motivation

The physical properties of snow in the Arctic environment play an important role for the surface energy balance. There are several reasons why scientists are interested in high-resolution snow-temperature data: Both the spatial and temporal distributions are directly connected with the energy balance at the atmosphere-soil interface. Regional changes in the thermodynamic properties of the snow may reflect climate-change processes and in parallel enable for prediction of them. Condition and changes of the snowpack can also affect the survival conditions for animals and plants, both those that depend on snow-free tundra and those depending on snow being present. Further, temperature data measured manually and automatically in snow are often required and used in snow models (*e.g.*, SNTHERM.89, Jordan, 1991). Whereas temperature measurements in deeper snow turned out to be less complex, near-surface measurements are especially affected by radiation influence/sensor heating and melt-water percolation.

1.2. History

Despite snow (pit) temperature measurements are a kind of a standard measurement within glaciology and snow hydrology, very little research focused so far on the technical problems when measuring temperature of snow near the surface. Automatic measurements using fixed sensors and data loggers are also exposed to possible errors. The aspect of stabilization of measurements after bringing temperature sensors into the snow environment was discussed by Seppälä (1992). The fact that solar radiation may lead to higher temperatures in the snow near the surface while air temperatures are further below 0℃ ("greenhouse effect") is known and investigated (*e.g.*, Brandt and Warren, 1993; Liston *et al.*, 1999).

1.3. Aims

In this study, we aim at evaluating and quantifying measurement errors connected to both automatic and manual snow-temperature measurements as well as pointing out advantages and disadvantages of both methods, using data from a field campaign near Ny-Ålesund on Svalbard (Gerland *et al.*, 1999, 2000; Winther *et al.*, 1999, 2001). Data from manual temperature measurements during spring 1998 are compared with automatic measurements obtained with a thermistor string, installed in the field before the beginning of snow fall in summer 1997. In spring, temperature can be expected to vary much both on a spatial and a time scale.

2. Location

The measurements were taken 2 km west of the settlement Ny-Ålesund in a flat tundra area near the river Bayelva and the hill Leirhaugen. Ny-Ålesund is located at about 79°N ashore Kongsfjorden on the northwestern side of the Svalbard archipelago (Fig. 1). Despite its high Arctic location, due to a branch of the Gulf Stream, the climate on the western coast of Svalbard is relative mild. Because this location is favourable in many respects (local infrastructure, logistics) also studies from related fields like hydrology and soil science are going on in the same area (Harding and Lloyd, 1997; Sand and Bruland, 1999; Roth *et al.*, 1998). The site starts to be covered with snow in fall (earliest September, latest December); the snow is melting in June. The snow thickness at the end of the accumulation season (end of May 1998) was about 0.65 m (including a *ca.* 10 cm thick basal ice layer).

3. Instruments and measurements

Manual snow-temperature measurements were made every 2 or 3 days in snow pits immediately after digging. For that we used a portable electronic thermometer (Digitron 3204, Digitron Instrumentation Ltd., Hertford, England) with a metal Pt100 sensor/needle probe (length 13 cm, diameter 3 mm). The product maker calibrated the sensor and refers to an absolute accuracy of ±0.2℃. The measurements were done by inserting the needle probe into the snow wall of the pit that is closer to the sun, avoiding that the solar radiation affects the wall directly. Readings were taken after approximately 10–20 s, when temperature recording had stabilised. The vertical spacing between individual measurements was usually 5 cm, near the surface less. The measurements were always started near the surface at the uppermost measurement location. During the near-surface measurements a 20 cm × 30 cm

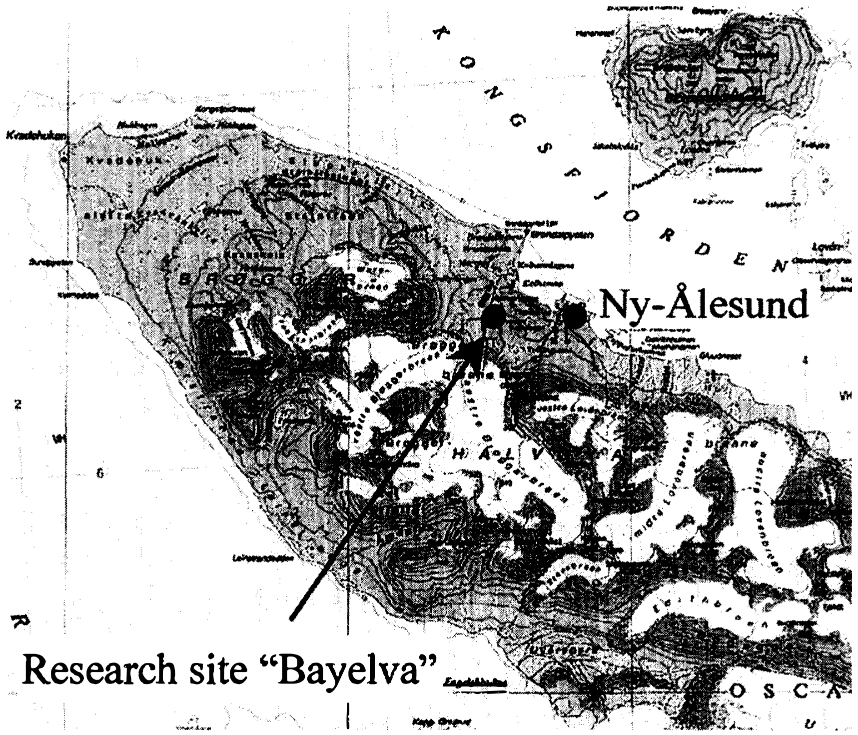

Fig. 1. Location map of research area. The research site located about 2 km west of Ny-Ålesund, Svalbard, it is marked by an arrow (map base: A7-Kongsfjorden, 1:100000, Norwegian Polar Institute, 1990).

plastic sheet was used to cover the surface above the measurement point in order to avoid direct heating of the sensor. As we intended to measure every time in pristine snow, we had to move the snow pit location slightly from day to day. Further, in order to keep the thermistor-string site operating and undisturbed, we had to dig the snowpits for the manual measurements in a distance of 10–20 m off that site. Due to locally varying snow covers, snow thicknesses for individual snow pits before beginning of melt varied by up to 10 cm.

Snow temperatures were measured automatically hourly with the help of a thermistor string (type TS-13ASV, Lakewood Systems Ltd., Edmonton, AB, Canada) and a data logger (type Lakewood R-X-16 data storing unit). The string was installed on a wooden stake during the snow-free season in 1997 with sensors placed at 0, 10, 25, 45 and 65 cm above the soil surface. Additionally, an air-temperature thermistor (type Lakewood R-XTP-5) was installed within a radiation shield at 2 m above the surface. The thermistors are placed within a plastic mantle (both outer length and diameter 2 cm, respectively), mounted on a cable (diameter 7 mm). The cable was fixed with cable ties directly to the stake, so that the sensors could not move relatively to the stake. In order to reduce heating by solar radiation, the cable and sensors were covered with white paint. The absolute accuracy of the thermistors after information of the producer is ±0.4℃. Next to the thermistor string, an automatic ultrasonic snow-level sensor (type SR50, Campbell Scientific Ltd., Shepshed, United Kingdom) registered the level of the snow surface relative to the sensor mounting hourly. The data were stored on a Campbell CR500 data logger. With the help of these measurements, we were able to determine the snow thickness and the distance between the individual thermistors and the surface for all measurements.

The two systems for manual and automatic measurements were not absolutely calibrated versus each other after purchase. However, in the context of this paper, the emphasis lays on the comparison of relative temperature variations with time and space.

4. Results

Manual temperature measurements in snow pits (Fig. 2) every other day show how the warm air heats the snow over time and how the snow temperature increases with time deeper into the snow pack. On 6 June 1998, temperature decreases more or less linear with depth, as it is typical for this location just before the onset of melt. By 14 June, the entire snow pack is in an isothermal condition. Surface-snow temperatures vary for different days only within 0.2℃.

The temperature time-series dataset measured with the thermistor string (Fig. 3a) gives only values at four different levels in the snow pack, but the relatively high temporal resolution shows the gradients with time at these levels more accurately. From 7 June 1998 onwards, the air temperature stayed more or less permanently above 0℃, therefore we took this date as the time of "onset of melt". This is about one week before snow temperatures reach the state of equi-temperature (Fig. 2). In the time series from automatic measurements (Fig. 3a), we further see the diurnal temperature variations in near-surface snow layers, which cannot be identified in our snow pit data (but are overlaid them). The sensor at 45 cm above soil surface shows these variations already before the onset of melt, whereas the sensors deeper in the snow are only affected for a short time between onset of melt and

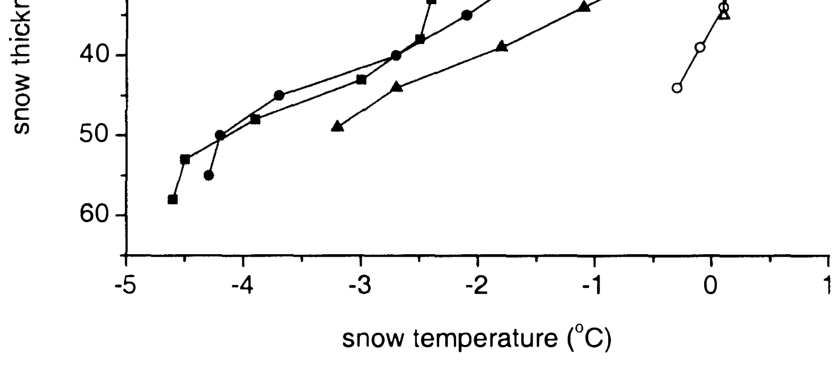

Fig. 2. Snow-pit temperatures from spring 1998, from 6 to 14 June 1998 every other day. The location of the snow pit was changed from one observation day to the next by a few metres in order to measure in pristine snow.

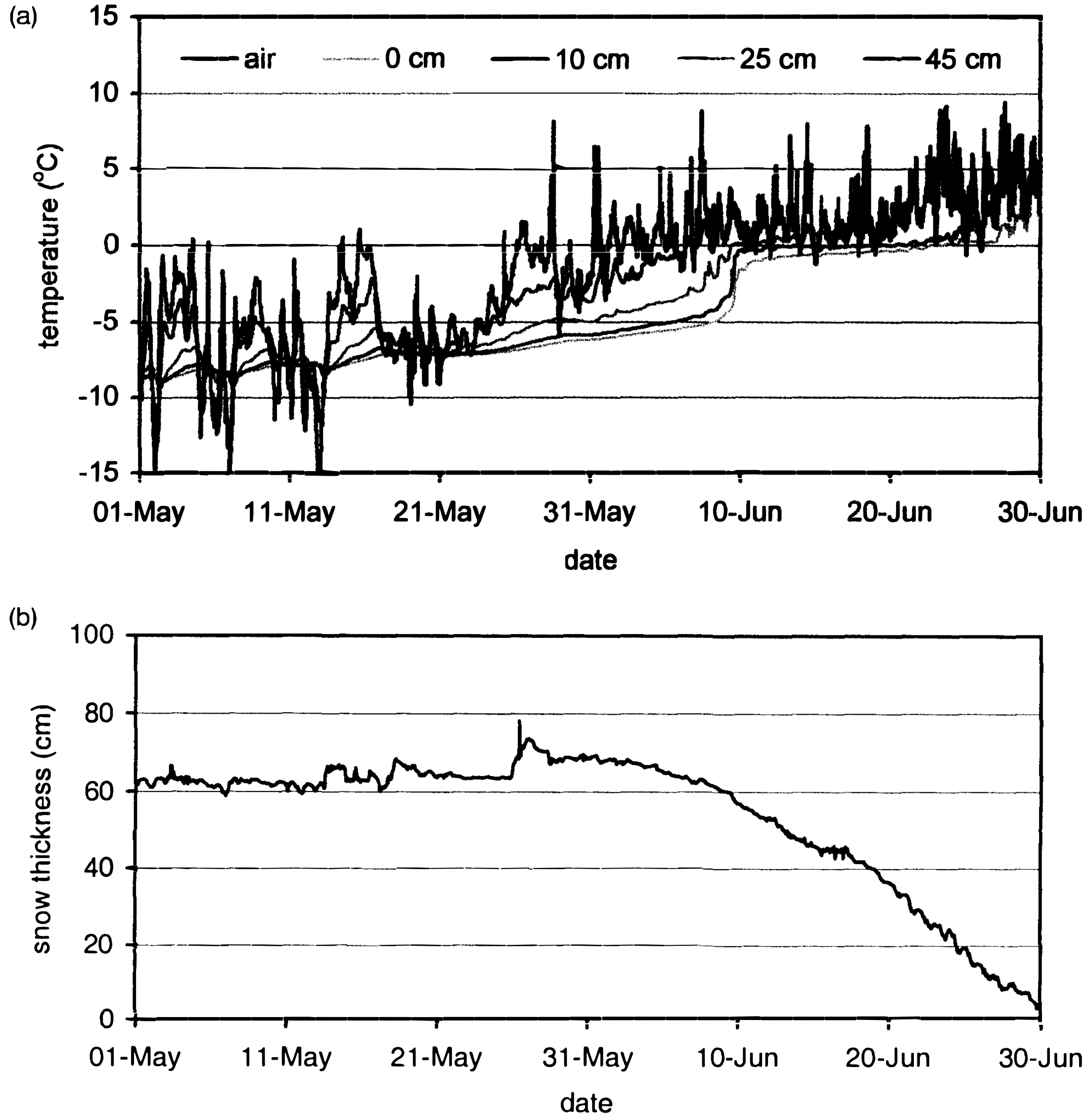

Fig. 3. Time series from spring 1998 with air temperature and thermistor-string data (a), and snow thickness (b). The snow thickness is calculated from automatic snow-level measurements next to the thermistor string.

temperature equilibrium. The development of snow thickness (Fig. 3b) shows a characteristic slope with decreasing snow thickness, after the melting has started. Further, gradual decreasing of snow-thicknesses after fresh snowfalls (settling, wind transport) is recognisable.

In Fig. 4 we show further manual measurements, here also from May, this time in order to compare them with automatic temperature logging.

5. Discussion

In-situ snow-temperature measurements can be disturbed by solar radiation and heat

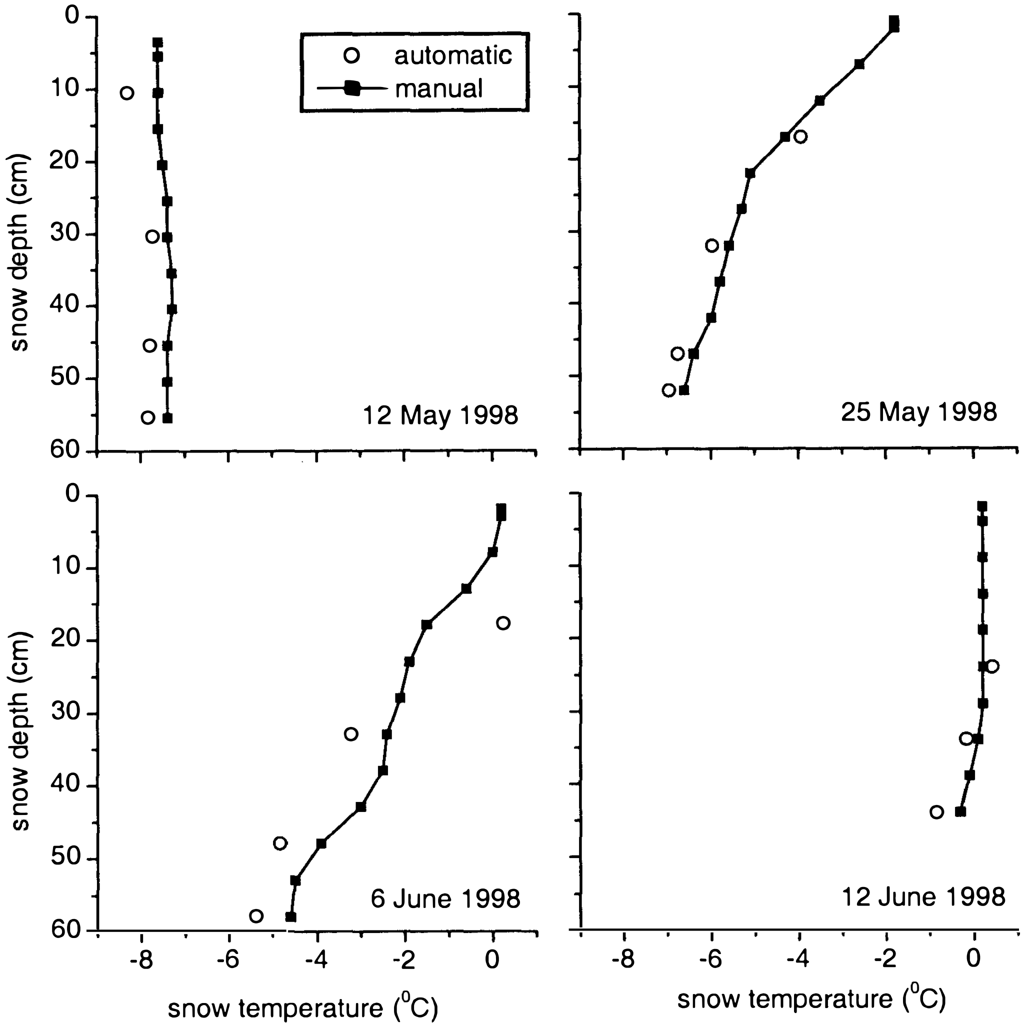

Fig. 4. *Comparison of manual and automatic measurements (from 12 and 25 May, 6 and 12 June 1998). Where the snow thickness for pits and the thermistor-string spot varied slightly, depths were corrected linearly in order to be able to compare both datasets. Near-surface thermistors show higher temperatures than snow-pit data already before the onset of melt.*

transport by migration of air or liquid water. In this research note, we want to focus most on the disturbances caused by solar radiation. Because of the plastic sheet used in connection with manual near-surface measurements, these readings are less affected by solar radiation. However, even with shadowing the snow above the sensor, manual measurements show systematically too high values (+0.2°C) near the surface; this could be due to scattered solar radiation, which reaches the needle probe from the sides, despite of the plastic sheet above. The sensors of the thermistor string are at all times exposed to potential heating by scattered solar radiation penetrating the snow. Accordingly, when comparing manual and automatic measurements (Fig. 4), the near-surface thermistors show higher temperatures than snowpit data for 25 May, 6 and 12 June 1998. The fact that this is not the case for our measurements on 12 May is probably connected to a lower sun angle and less transparent snow earlier in the season (Gerland *et al.*, 2000). The increase of snow transparency during spring, connected to snow metamorphosis, is a known effect. Modelling and measurements showed that after the onset of melt, solar radiation in the Photosynthetically Active Radiation range (PAR, 400–700 nm wavelength) can exhibit still 5% of the surface intensity at 20 cm depth (Gerland *et al.*, 2000). The comparison of measurement from 12 June 1998 shows that the depth down to where automatic measurements were affected by scattered solar radiation was at least 25 cm. Before the onset of melt, solar radiation is attenuated to the 5%-level already at 10-cm depth. The offset of about 0.2°C in absolute temperature at deeper levels (Fig. 4) might be either showing the limit of instrument calibrations and accuracy, or it is connected to scattering light from the snow-pit walls, penetrating the snow and heating the sensor.

Looking more in general on the heat balance at a temperature sensor within the snowpack, the situation can be described by the differential equation

$$C\frac{dT}{dt} = -k(T_m - T_s) + R,$$

with C as the heat capacity, T_m as the measured temperature at a certain time t, T_s as the snow temperature, k as the conductivity coefficient that is influenced by the coupling between the sensor and the surrounding snow, and R representing net radiation. The net radiation depends on incoming and reflected solar radiation, snow transparency, sensor depth, and sensor albedo. In theory, if the temperature measurements could be performed without radiation influence, the measured temperature would equal the snow temperature after a certain time (depending on k and difference between the initial sensor temperature and snow temperature). However, in reality the net radiation disturbs the measurements more or less. Sensor designs providing good thermal coupling to the surrounding snow and high sensor albedo in combination with a measurement setup with only little or reduced radiation influence will improve the measurement results.

From our comparison and the nature of the instrument setups of manual and automatic snow temperature measurements, we can summarise advantages and disadvantages (see also Table 1): An advantage of manual measurements is that the spatial resolution can be chosen as high as desired, disturbing effects from solar radiation can be partly excluded, and the snow layering is undisturbed from the setup. Further, parallel snow pit measurements of other physical and structural snow properties may ease the interpretation of the data measured. On the other hand, a plus of automatic measurements is that they are

Table 1. Advantages (+) and disadvantages (−) of manual and automatic snow temperature measurements.

Aspect	Manual measurement	Automatic measurement
Time resolution	−	++
Depth resolution	++	+
Areal resolution	+	−
Destructiveness	−−	+
Solar rad. disturbance	−	−−
Time and manpower	−	+

non-destructive, and therefore measurements are possible at exactly the same location over longer times. Automatic measurements enable further to measure snow temperatures at high resolution in time, such that diurnal changes and fast temperature changes can be recorded and investigated. Substantial disadvantages of automatic measurements are the possible effects of solar radiation, especially near the surface, and possible heat and water transport along the string cable. The thermistor string setup itself might also disturb and alter the snow layering and melting. Areal measurements comparable to regional snow-pit studies are usually limited because of logistic and financial reasons, which do not allow to install as many thermistor strings in one area as desired. Manual measurements on the other hand require more time and manpower and their destructiveness set limits for certain monitoring studies. The experiments further showed that also snow-pit measurements are affected by solar radiation. A major disadvantage of manual snow temperature measurements in pits is the low temporal resolution. The "snapshot" character of the data hides diurnal and weather-dependent temperature variations (*e.g.*, cooling at night, warming during day). Possible misinterpretation can only be avoided by having time series with high temporal resolution.

6. Conclusions

In the lower part of the snowpack, automatic measurements with hourly time resolution reproduce snow temperatures above Arctic tundra in general well, as it could be confirmed by snow pit reference measurements. However, especially near the surface, manual and automatic measurements of snow temperature may contain inaccuracies caused by different error sources (*e.g.*, sensor heating by solar radiation, distortions by the measurement setup). It is not possible to conclude that one method consistently is more accurate than the other. The biggest advantage of automatic measurements is the high temporal resolution, which makes this method suitable for long-term monitoring studies, and which resolves fast, diurnal temperature changes. On the other hand, within surveys over larger areas in order to cover spatial variations of snow parameters, manual measurements are usually the only affordable option. Further, snow-pit studies enable snow scientists to do *in-situ* multi-parameter studies including sampling and subsequent sample analysis.

If one wants to minimise the disadvantages of each method, a combined use of automatic and manual measurements is optimal. For example, a few automatic sites could help within a regional study to correct snow-pit data for daily temperature variations, or snow-pit surveys could be used to correct near-surface thermistor-string temperature data for solar-radiation influence. While using thermistor strings for snow temperature monitoring in remote areas, simultaneous automatic snow-thickness measurements help to define the distance between individual sensors and the snow surface. This information is necessary to evaluate logged temperature data for possible errors connected with solar radiation.

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