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The application of an instrument for non-destructive measurements of soil temperature and resistance profiles at a high Arctic field site

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Abstract

An easily constructed and installed instrument for measuring colocated soil temperature and resistance profiles is described. Minimum disturbance to the soil structure is achieved. The system indicates the melting front of permafrost at a high Arctic field site and shows the effect and extent of summer rainfall events upon the soil water profile. The system is capable of long-term recording of soil moisture profiles at a frequency commensurate with eddy correlation measurements of the surface fluxes of water vapour and carbon dioxide; it thus provides the information necessary for understanding the processes involved in the soil-atmosphere exchange of water and carbon dioxide.

Introduction

An investigation of the energy, water and carbon balance of an Arctic site, subject to seasonal permafrost, requires a measurement of the depth to which thawing of the permafrost has occurred during the summer. The effective exchange of heat, moisture and carbon dioxide during the short summer period occurs in this active soil and vegetation layer above the largely impermeable permafrost layer. In a biome where the soil is as important as the vegetation in providing sources and sinks for moisture and carbon dioxide, the thermal and moisture changes in the soil must be determined as often as the flux of moisture and carbon dioxide from the surface. Furthermore, in organic soils consisting of saturated and drying soil layers above an impermeable layer, be it rock or permafrost, knowledge of the depth of saturated and of unsaturated soil is essential to an understanding of the carbon dioxide and methane fluxes measured above the surface.

Current methods of measuring freezing depth and soil moisture profiles suffer from several disadvantages. The neutron probe method lacks the precision for near-surface measurements while capacitance probes are still largely unautomated. Time Domain Reflectometry (TDR) can provide measurements of freezing fronts and soil moisture but the method is expensive and can create large datasets with consequent time consuming analysis if complete waveforms (required for identification of the freezing front) are taken. There is also conflict between vertical positioning of the TDR probes for freezing front measurements and the preferred horizontal positioning of the TDR probes for soil moisture measurements which also creates some disruption to the soil structure. Gypsum blocks and glass fibre resistance units degrade, create disruption of the soil structure in their installation, and are not robust enough to withstand freezing.

Generally, any soil sensor installation, other than those near the surface, will involve some, often major, disturbance to the soil structure immediately surrounding the measurement position. Such disturbance, often involving trenching and subsequent back-filling, will affect both the thermal and moisture gradients. While some soil types and horizons may return to something approaching the original state after disturbance, clay soils and cold or perennially frozen soils, such as encountered in tundra regions, may take decades to return to their original state.

The measurement of freezing fronts in soils using soil temperature and soil resistivity is well known. However, the 0°C position in soil temperature profiles does not necessarily identify where the soil becomes frozen—as pointed out by Bouyoucos (1921), Post and Dreibelbis (1942), and Anderson and Tice (1970), who detected liquid water in soils at temperatures well below freezing point. There is a marked change in electrical resistivity of soil during freezing and thawing e.g. see Colman and Hendrix, (1949), and Sartz, (1967) who used glass fibre resistivity units to measure the electrical resistance between two plates separated by a glass fibre cloth, the whole unit assumed to be in thermal and moisture equilibrium with the surrounding soil. However, installation of these units was achieved by Sartz (1967) only by augering 0.1 m holes, which were backfilled after installing the sensors. There was considerable soil disturbance and the glass fibre cloth also had a limited lifetime.

The measurement of temperature and resistivity in tundra soils requires an instrument capable of accurate and variable positioning and separation of sensor depths; of easy installation of sensor units in remote locations with little disturbance to a fragile soil structure; of long term operation and able to withstand the physical pressures of freezing soils and of measuring and recording data routinely at time averages from 10 minutes to 24 hours over periods of weeks, months or years.

Four types of soil temperature and soil resistivity profile units were described by Banner and van Everdingen, (1979), each successive type building on the lessons learnt in the previous ones. However, their final version still required power-augered holes of up to 0.23 m diameter, which were subsequently backfilled and they observed that poor backfilling produced poor electrical contact.

This paper describes the design, materials and fabrication details of an improved temperature and resistivity sensor unit together with data logging specifications and presents results from its use in an Arctic soil in Svalbard. The advantages and limitations of this device are discussed.

Instrument design

The instrument consists of a rigid hollow tube of circular cross-section of about 20mm, comprising narrow section brass rings separated by rigid plastic spacers. Each ring has an embedded thermocouple and a separate low-loss signal lead. The brass rings are held rigidly between the threaded plastic spacers. The whole unit is waterproof. Temperature at each brass ring position and resistance through the soil matrix situated between and around adjacent rings are measured via a multiplexer attached to a controlling datalogger.

THE PROFILE SENSOR ARRAY

Figure 1 shows a single disassembled measurement ring joint together with a plan view of the brass ring and a schematic of the profile assembly used in this paper for measurements in the surface 250 mm. The profile unit consists of 22mm outside diameter (o.d.). annular Naval brass (chosen for its good corrosion resistance, easy machinability and high thermal and electrical conductivities) rings (code BS 2874/CZ–112) separated by 21 mm o.d. PVC-U tubes of very low thermal and electrical conductivity, low linear expansion, and good weather resistance and tensile strength. The brass was chosen in preference to stainless steel because of its higher thermal and electrical conductivity, although it was recognised that tarnishing of the surface might lead to higher electrical resistance over time. Subsequent profile units had very thin chrome plating applied to the brass rings to overcome this tendency. The smaller diameter of the spacers eased installation in augered 22 mm holes and the larger diameter and annular form of the rings improved the chances of good contact between the soil surface and the rings once installed. At their ends, the tubes have male and female screw threads which, with silicone sealant, creates a waterproof joint between the tubes and the intervening brass ring. The PVC tubes can be of any required length above 25mm. Profile arrays of 1 m length have been installed successfully and probes of up to 2 m in length should present little difficulty in installation or operation The brass rings have two inside flanges which slot into the PVC tube and provide extra strength, and prevent twisting of the joint. They also provide the housing for a Teflon-sheathed 0.5 mm diameter Copper-Constantan thermocouple (part no. 5TC-TT-T–24–72, Omega Engineering, Broughton Astley, UK,) and, diametrically opposite, a brazed-in tag for soldered connection of the soil resistivity signal wire. The thermocouple is embedded and glued into a 1.6 mm hole using an epoxy resin capable of providing adhesion and strength at temperatures well below zero and with high thermal conductivity and low electrical conductivity (Part no. OB-CY20–2/–5, Newport Electronics, Broughton Astley,UK). When embedding the thermocouples, continuity checks were performed to ensure that no part of the exposed thermocouple bead was in contact with the brass ring. The thermocouple and the resistivity wire are therefore isolated electrically. A maximum of sixteen rings is limited by the the number of thermocouple and signal wires that can be accommodated within the PVC tube. The thermocouple and resistivity wires are fed through individual holes in sealing plates on either side of a 50 mm PVC-U head-unit, which is sealed by an O-ring onto the profile array. The size and mass of the head allows hand pressure, or judicious use of a soft hammer, for installation.

DATA LOGGING

The data were logged using an AM416 Multiplexer unit and a CR10 logger (Campbell Scientific, Shepshed, UK). In this paper the AM416 multiplexed two 8-level profile units to two differential analogue input pairs on the CR10 logger. Up to three multiplexer units can be accommodated by the CR10 logger, allowing six profile units to be logged. A 10CRT thermistor probe (Campbell Scientific, Shepshed, UK) in thermal contact with the AM416 provides the external reference temperature for the thermocouple measurements. The CR10 and AM416 are contained within a common insulated box to reduce the

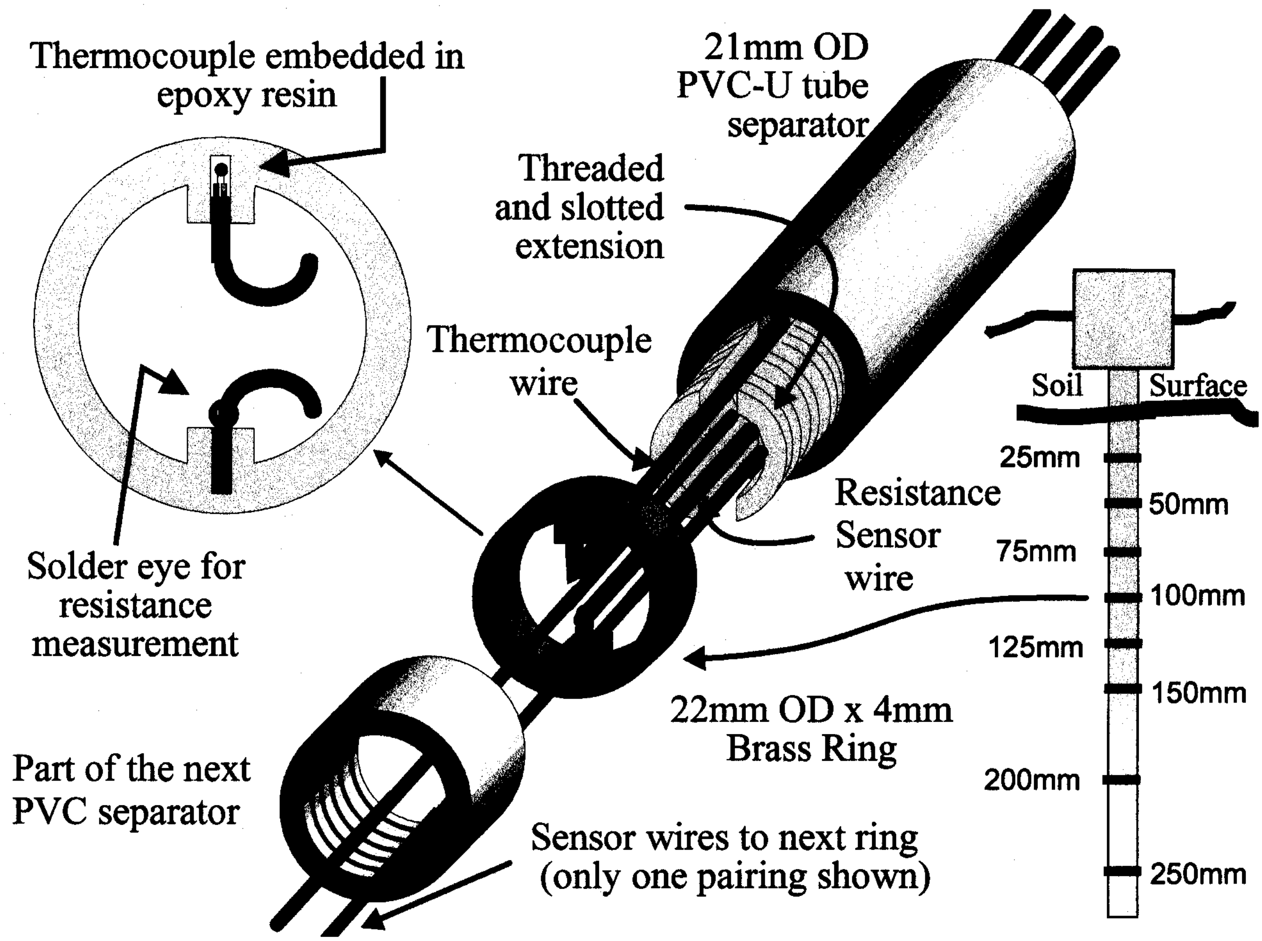

Fig. 1. *Schematic diagrams of the location of the thermocouple and resistance sensor wire within the brass ring, an exploded view of a single measurement joint and a complete profile sensor array within the soil.*

effects of external temperature gradients on the soil measurements. The soil resistivity measurements are made sequentially between adjacent rings, i.e. between ring 1 and 2, then between 2 and 3, etc. This is made possible by the isolating switching relays on the AM416. The CR10 uses an AC half bridge measurement instruction and a bridge transform instruction to convert the signal voltage measured across the soil matrix contained between adjacent rings to a soil resistance value. Rapid switching of this circuit limits polarisation of the rings. Although measurements can be taken automatically every 10 seconds (the time it takes for a complete cycle of measurements to go through the multiplexer), it was adequate for this application to take hourly measurements which were then stored, together with a daily average. The multiplexer and data logger were powered by a 12V sealed lead-acid battery with solar panel charging. Fig. 2 shows a complete prototype two profile unit assembly before installation. This assembly has 100mm and 25mm spacing on the profile units and chrome plated rings. The logger box would be placed in an insulated waterproof box for field operation.

Field application

INSTALLATION

The soil profile arrays were deployed as part of a larger experiment investigating the relationship between the water vapour, heat and carbon dioxide fluxes, and the heat and moisture gradients in the saturated and unsaturated soil layers above the permafrost. This experiment and site was in the glacier-fed Bayelva river valley close to Ny-Ålesund in Svalbard (78°56′N, 11°55′E). The area is on the border between the Middle Arctic Tundra Zone and the Northern Arctic Tundra Zone (Elvebakk, 1985) and has areas which are polar semi-desert. The site is typical northern Tundra and is described as 100–50% *Luzula* lichen heath (Brattbakk, 1981) on a clay silt soil with a 20 mm organic cover.

Ideally, soil profile units should be installed in the previous autumn to allow early spring measurement of the freezing depth. Unfortunately, the above-ground cables from the profile units installed in the autumn of 1994 were damaged by reindeer during the late autumn and it was necessary to reinstall a 0.25m profile unit on 13 June 1995.

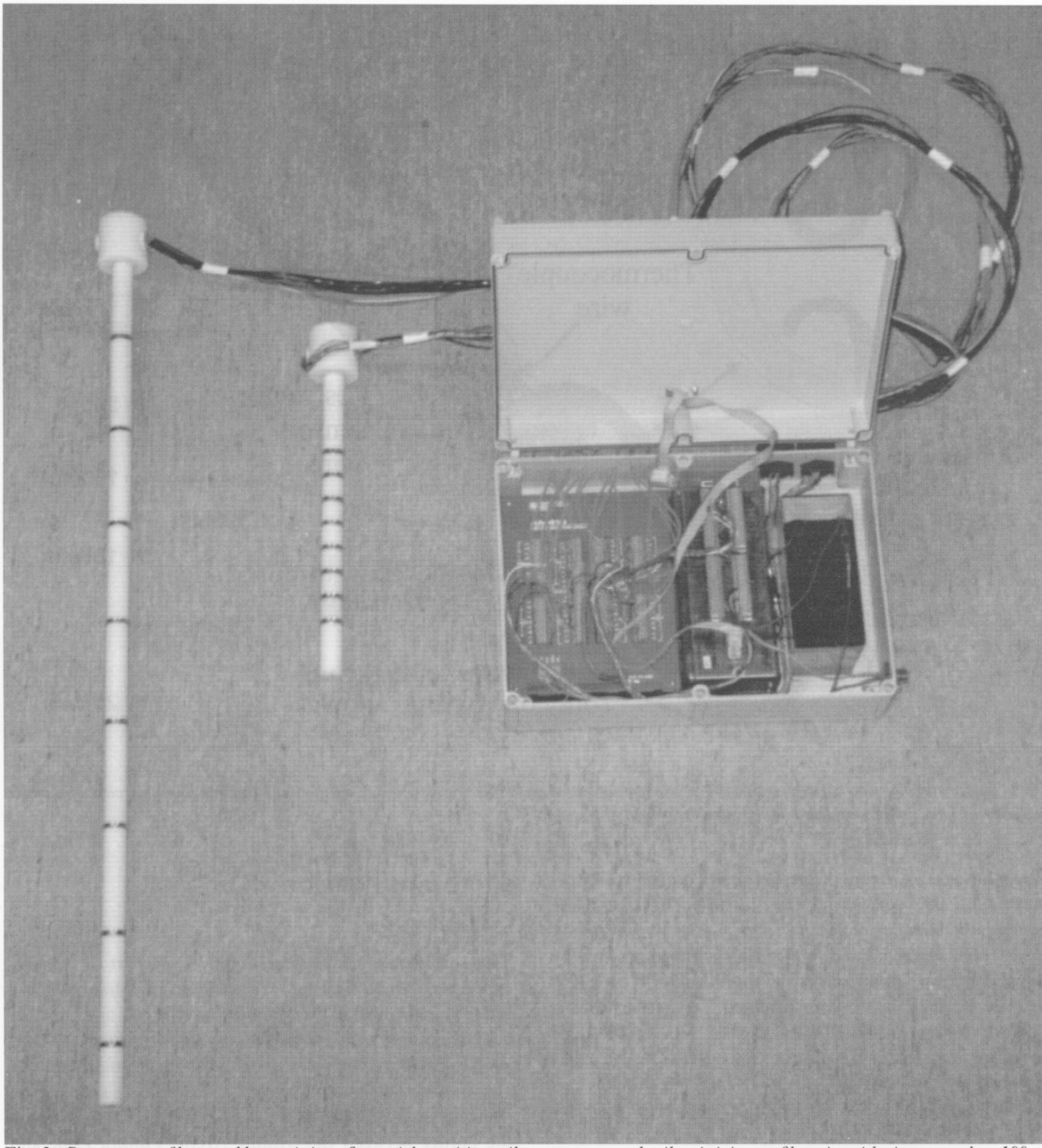

Fig. 2. *Prototype profile assembly consisting of two eight-position soil temperature and soil resistivity profile units with rings spaced at 100mm and 25mm. The logger box contains the AM416 Multiplexer, CR10 data logger and 12V battery.*

This shorter unit was used at this time because permafrost is difficult to auger. A hole was made using a 22 mm wood auger welded to a short length of 18mm rod. Drilling to greater depths involved screwing 0.5 m lengths of extension rod onto the wood drill. The hole was hand augered for better precision. The profile unit was then pushed carefully into the hole using hand pressure alone.

Results

Colman and Hendrix (1949) showed that resistance values were sensitive to temperature and soil water content. They also showed in the production of calibration curves of resistance values for varying soil water content and temperature that while absolute resistance values varied with soil type, the slope of the lines relating temperature to resistance and soil moisture to resistance were very similar. Following this work, Seyfried (1993) used a simple linear temperature correction based on a single water content value, justifying this because the temperature fluctuations in his data were relatively small and the effect on the estimate of the soil water content was minimal. The resistance values in this paper have been corrected using the linear value of $-0.0154\ k\Omega\ K^{-1}$ found by Seyfried (1993). The temperature used was the mean of the two temperatures bracketing the resistance measurement. Figure 3 shows the diurnal change in the temperature and the soil resistivity profiles during the first few days after installation. Just after installation, at this late stage of the thaw, only the soil below 125 mm is at a temperature below 0°C. Temperature considerations alone imply that the soil is still frozen below 125mm on the 13 June, a conjecture confirmed by examining the diurnal resistances for these positions. The resistances are relatively high at the beginning of the trace, indicating frozen soil, but decrease rapidly to the unfrozen resistance values of about 2.5 $k\Omega$ as the temperature rises above the 0°C line. Note that the resistance values for the lowest two inter-ring distances are over an interval of 50 mm compared to 25 mm for the rest of the profile. The temperature profile also shows a gradient of nearly 10°C over a depth of 250 mm. Simple resistance graphs like Fig. 3 indicate the progression of thawing in the soil very effectively.

Once the soil has thawed, the soil resistance traces indicate soil moisture content over time and provide insight into ongoing soil processes. Figure 4 shows the temperature and soil resistance values for a week following the thawing events shown above, together with the 0.5 mm tips recorded by the raingauge attached to a nearby Automatic Weather Station (AWS). Three depths have been chosen from each of the profiles to show the following:

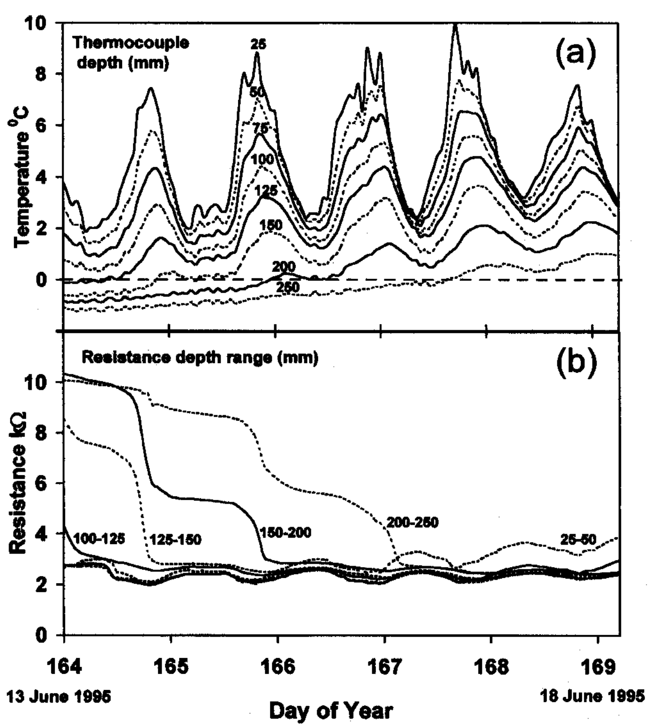

Fig. 3. *Diurnal changes in soil temperature (a) and soil resistance (b) for the period 13–18 June 1995.*

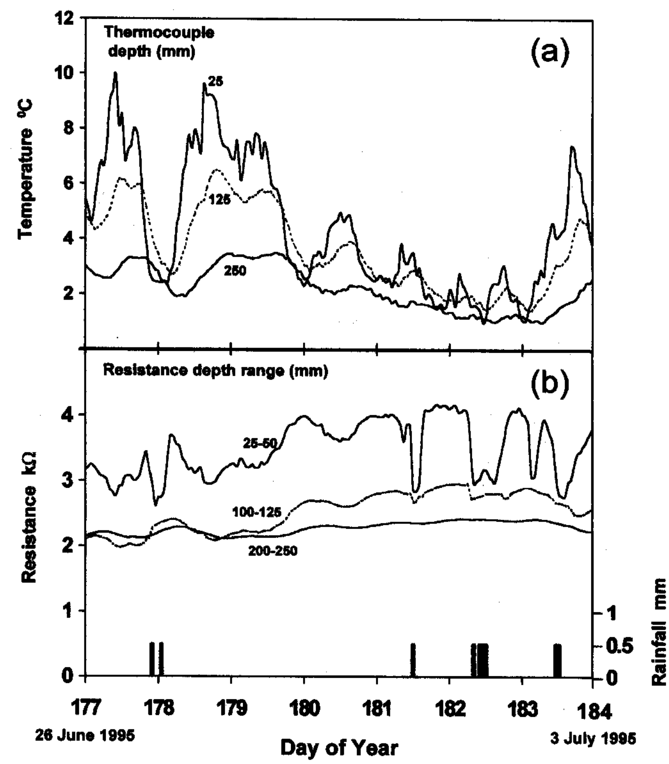

Fig. 4. *Diurnal changes in soil temperature (a) and soil resistance (b) following rainfall events for the period 26 June–2 July 1995.*

(i) the rainfall produced significant reductions in the soil resistance values from the surface down to 125 mm, the lowest point in the profile that could be regarded as responding to the rainfall events,

(ii) soil below this point did not change significantly in response to the rainfall events although it did respond gradually to the changing soil moisture,

(iii) the top 25 mm of soil dried very rapidly after cessation of rainfall.

The rainfall event apparently 'seen' by the 25–50mm soil resistance measurement on the night of 1–2 July (day numbers 182–183) is most probably real but was less than the 0.5 mm needed to cause the bucket to tip.

While Fig. 4 illustrates the way in which soil resistance values can indicate relative qualitative changes in soil moisture at different depths, water balance and process studies require absolute moisture values. The soil at this site was therefore calibrated. A 0.8 kg sample from a soil monolith taken from an area adjacent to that in which the field sensors were installed was dried at 105°C for 24 hours. The sample was taken from the middle of the monolith approximately 100mm below the shallow organic layer. The sample was then crushed and any stones removed. The resultant soil had a dry bulk density of 1234.3 kg m^{-3}. A 100mm diameter open ended plastic drainage tube 100mm long was sealed onto a plastic chamber which had a sintered ceramic disc as the interface between the chamber and the soil sample tube. A 5mm layer of very fine washed and dried sand (dry bulk density of 1399 kg m^{-3}) was spread evenly across the ceramic disc to prevent clogging of the ceramic. The sand had a porosity of 0.48, close to that of 0.53 for the sample soil. Both materials therefore had similar moisture holding properties. A 15mm layer of the crushed clay soil was spread evenly on the sand. A resistance unit comprising 2 brass rings sealed to either end of a specially made solid 25mm profile separator was placed horizontally on the soil surface. Further clay soil was then spread around and over the resistance unit so that a further 15mm of soil covered the unit. The entire calibration rig was vibrated to ensure close packing of the soil particles. The wires from the resistance unit were attached to an AM416 Multiplexer and CR10 logger similar to that used in the field. A thermistor was installed in the outer edge of the soil layer at the depth of the middle of the resistance unit. Weights and volumes of soil, sand and resistance unit were recorded as was the weight of the entire calibration rig. The rig was supported on a balance which showed the change in weight due to changing moisture levels in the soil layer. The entire unit was then wet from the bottom up by applying a positive head of distilled water into the lower chamber. Distilled water was used as the field soil had a pH of 6.5. As soon as a film of water appeared on the surface of the soil, wetting up was terminated and water in the lower chamber was removed leaving an isolated soil layer close to saturation. The soil layer was allowed to dry naturally from the upper surface over a period of 2 weeks during which time soil temperature, soil resistance and calibration rig weight were recorded on a near daily basis. Figure 5 shows the calibration curve for this soil; logarithmic percentage gravimetric moisture content is plotted versus the logarithm of resistance. A similar relationship was found to apply to high clay-content soils by Reynolds *et al.* (1987) with some evidence of similar curvature. Bouyoucos and Mick, (1948) also found a non-linear relationship between the logarithm of resistance in glass fibre units and soil moisture across a wide range of soil types. Gupta and Hanks (1972) found a linear relationship between soil conductivity and moisture content in sandy and silty loam soils; this implies a non-linear relationship between soil resistance and soil moisture. It is interesting to speculate on the interpretation of the apparent increase in soil moisture values at constant resistances shown on the left hand side of the figure. The turning point may indicate the minimum surface moisture film on soil particles required to provide a continuous water path through the soil matrix. Under such a hypothesis additional soil moisture will not decrease this resistance.

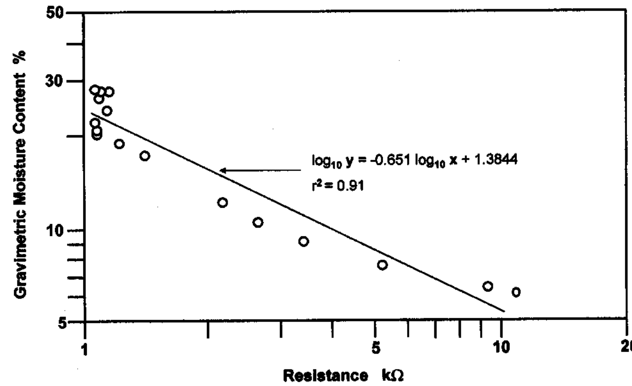

Fig. 5. *Soil resistance versus gravimetric soil moisture calibration curve and fitted equation for the soil at the Ny-Ålesund site.*

Using the linear regression equation for this calibration, values of resistance for the whole summer were converted to volumetric water content. The resistance values for the 50mm separation between 200–250mm was halved before applying the calibration. Figure 6 shows these moisture values and associated soil temperatures for specific depths, selected for clarity and to illustrate seasonal effects at important depths in the soil profile. The gap in the data was due to operator error in retrieving the data from the CR10 logger. The upper graph shows increasing and decreasing soil temperatures at the top and bottom of the profile associated with average diurnal ranges of approximately 6°C and 0.5°C respectively. The gradual rise in soil temperature during the post melt period is evident. This is followed by a period of generally constant temperature during the summer and then a gradual temperature drop as autumn approached. From this graph, the lowest level, at 250 mm, is expected to re-freeze on or about 5 September.

The lower graph, of seasonal variation in soil moisture, shows the effect of precipitation on the upper 125 mm of soil with only gradual and lagged response to this moisture addition being shown lower in the profile. The graph also shows the increasing gradient of soil moisture over the summer period with the lowest measurement staying relatively wet with increasing drying of the soil above this point. This drying of the soil profile confirms the results from the eddy correlation measurements during the same period, where evaporation from this site was nearly twice the rainfall. The evidence from both graphs indicates that refreezing of the entire profile during the year will probably occur in soil drier than that on average occurring during the summer.

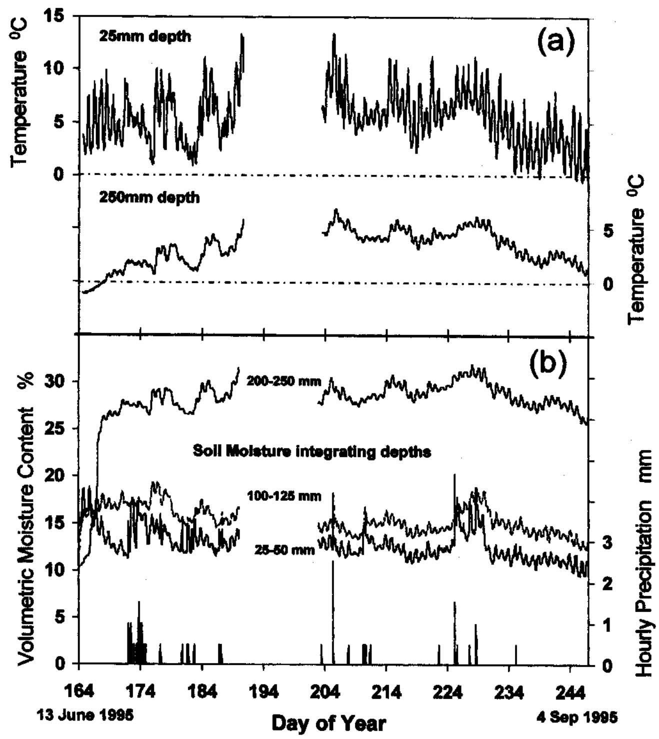

Fig. 6. *Soil temperatures (a) and soil moisture values (b) for selected depths in the soil and rainfall for the active summer period between the spring thaw and the autumn freeze.*

Discussion and conclusion

This method is inexpensive, robust, capable of operating unattended in harsh conditions and causes minimal physical change to the soil profile whose thermal and moisture properties are being investigated. The single narrow augered hole limits disturbance of the soil horizons in most soils, except those containing many stones or gravel, although these also present problems in measuring soil resistance and soil moisture by other methods. The robust profile system can be assembled and tested in the laboratory and rapidly and simply installed in the field. There is limited degradation of the soil profile units once installed, and the use of corrosion resistant naval brass and unpolarised resistance measurements allows their use in highly acidic soils. Current versions of the rings are plated with a thin chromium layer to limit corrosion even further with minimal increase in ring resistance. The use of oversize annular rings increases the possible contact area and provides contact points even in non-straight augered holes. As all the possible resistance paths between adjacent rings are in parallel, the overall resistance value is dominated by the lowest value—provided by the best ring-soil contact point.Criticism of measuring soil resistances between electrodes (as opposed to resistivity of material in potential equilibrium with the soil i.e. gypsum blocks and glass fibre units) centres mainly on the effect of ion concentration on the absolute value of soil resistivity (Schmugge *et al.*, 1980). This problem will limit the method where ionic concentration in the soil changes either in time or over the depth of the profile. Careful calibration is then required to ensure that real changes in soil moisture are not confounded with changes in the resistance due to ionic concentration changes.

For this reason, the use of soil resistance to measure soil moisture has lost favour in recent years, as neutron probe, gamma ray attenuation, soil capacitance and TDR methods have come to the fore. However, none of these methods permit inexpensive, frequent and long-term automatic measurements of combined and co-located soil temperature and soil moisture in the important surface soil layers, measurements of which are vital to the understanding of the soil-vegetation-atmosphere transfer of heat and moisture. The robustness of this application of the resistance method makes it especially suitable for unattended operation in harsh, remote field sites such as are encountered in the Arctic.

Acknowledgements

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