Soil moisture measurement in the Ross Sea region of Antarctica using Hydra soil moisture probes

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Abstract
The objectives of this study were to determine the limitations of Hydra soil moisture probes (Stevens Water Monitoring Systems Inc., Oregon, U.S.A.) for use in Antarctica and to describe the soil moisture regimes of soils located at Scott Base, Marble Point and in the Wright Valley.

Laboratory and field experiments were undertaken to compare Hydra probe soil moisture measurements with gravimetric soil moisture measurements. Once the limitations of the probes were determined Hydra probe data from three Antarctic sites over three years were analysed. Laboratory and field experiments showed that soil temperature, texture, and salinity all influenced the soil moisture results recorded by the Hydra probes. The interacting effects of soil texture, temperature and salinity were found to be generally within the ±3% limit of accuracy of the Hydra probe stated by the manufacturers.

Up to five soil-moistening events were identified each summer at Scott Base and Marble Point, while in the Wright Valley soil-moistening was detected once, by one sensor, over three summers. Maximum volumetric liquid soil moisture contents of 23% at Scott Base, 32% at Marble Point, and 6% in the Wright Valley were recorded. At the 2 cm depth, the liquid soil moisture was >5% for a cumulative average of 860 hours each summer at Scott Base, 1 hour in the Wright Valley, and 310 hours at Marble Point. The drying period following soil-moistening for surface soils (2-5 cm depth) was about 6 days, which was extended to about 12 days when freeze-thaw cycles were occurring.

Key Words
Hydra soil moisture probe, dielectric constant, soil climate, cryosol, cold desert.

Introduction

In the cold desert environment of the McMurdo Dry Valleys region of Antarctica soil moisture plays an integral part in soil processes and biological activity, as well as being an indicator for climate change. Soils in the Ross Sea region of Antarctica predominantly comprise gravely sand materials with permafrost at depths of between about 20 and 80 cm. Soil moisture regimes in the Antarctic dry valleys have been previously studied (e.g. Campbell and Claridge 1969; 1982; Campbell *et al*. 1997; Campbell *et* al. 1998) however, data have been limited to gravimetric sampling over short summer periods. Near the soil surface gravimetric soil moisture contents are often less than 5% except for short periods when snowmelt occurs, or in areas adjacent to lakes or streams. The extent and duration of soil moisture availability has not previously been elucidated.

Gravimetric sampling for soil moisture content is labour intensive, destructive of the site, and can only be undertaken when people are present. The use of continuous data-logger supported measurement allows monitoring of the same site over extended periods so that changes over time and between seasons can be determined. Seven soil climate stations have been established in the Ross Sea Region of Antarctica to monitor soil moisture and temperature along with aboveground climate parameters (Balks *et al*. 2003).

Soil moisture was continuously monitored using Hydra soil moisture probes (Stevens Water Monitoring Systems Inc., Oregon, U.S.A.). The Hydra soil moisture probes make high frequency (50 MHz) complex dielectric constant measurements (Vitel Inc. 1994), which are used to determine the volumetric soil moisture content (θ_v-HP) (Stevens Water Monitoring Systems Inc. 2003). The Hydra soil moisture probes also measure the electrical conductivity of the soil in the range of 0-20 000 µS cm^{-1} and soil temperature in the range of –10 to +65°C. The dielectric constant of liquid soil water dominates the bulk dielectric constant of the soil (Jones *et al*. 2002). The dielectric constants of the main constituents of the soil are water (ε_w = ~81), air (ε_a = 1) and soil minerals (ε_s = 3–5) (Roth *et al*. 1990; Lide, 1997). Ice has a dielectric constant of 3.2 (Lide 1997), thus limiting the use of dielectric constants for determining volumetric soil moisture content to unfrozen soils. The measurement of the dielectric constant of the soil is affected by soil temperature (Ledieu *et al*. 1986; Roth *et al*. 1990; Pepin *et al*. 1995; Yu *et al*. 1999; Wraith and Or 1999), soil texture (Dirkson and Dasberg 1993; Or and Wraith 1999; Ponizovsky *et al*. 1999) and electrical conductivity and salinity (Nadler *et al*. 1999).

As the use of Hydra soil moisture probes, or other capacitance or TDR probes, has not been previously reported in the McMurdo region of Antarctica, this paper aims to investigate the operation of the Hydra soil moisture probe under Antarctic conditions. Hydra soil moisture probes were chosen as they are also used in comparable studies in the Arctic and Tibet giving us the opportunity for direct comparison with a global dataset. The effects of soil temperature, texture and electrical conductivity, on probe readings, were investigated. Once the limitations of the Hydra soil moisture probes, under Antarctic conditions, were determined, a second objective was to interpret and report soil moisture data from three soil climate stations.

Materials and methods

Moisture probe verification

In both laboratory and field experiments the volumetric soil moisture content was measured using the Hydra soil moisture probes (θ_v-HP) connected to a CR10X datalogger (Campbell Scientific Inc., Logan, Utah, U.S.A.) and compared with the volumetric soil moisture content calculated from gravimetric moisture content and soil dry bulk density (θ_v-GD). The gravimetric soil moisture content was determined using standard methods (McLaren and Cameron 1996). Soil dry bulk density was determined in the laboratory experiments using the core method (Blake and Hartge 1986) and in the field using sand replacement (Burke et al. 1986).

In the laboratory cores were packed with sand and gravel, as a substitute for Antarctic soil materials, at known moisture contents. A series of experiments were undertaken in which soil temperature, texture and salinity were varied. Details of the experimental designs are included in Wall (2004). In the field soil moisture was determined with the Hydra probe then the probe was removed and the area excavated to determine soil dry bulk density and sample for gravimetric moisture content determination.

Antarctic soil moisture measurements

Soil climate stations at Scott Base, Marble Point and in the Wright Valley (Table 1) measure soil moisture using Hydra soil moisture probes. Soil moisture measurements are made at depths of 2, 15, 25 and 40 cm at Scott Base, 2, 20, 50 and 80 cm at Marble Point, and 2, 20, 30, 50, and 120 cm in the Wright Valley. Soil moisture measurements are made every 20 minutes, and hourly averaged values were recorded for three complete summers (1999/2000, 2000/2001, and 2001/2002).

Table 1. Soil-climate station location and site description.

Station (date installed)	GPS Location (altitude m)	Site Geomorphology	Soil classification*
Scott Base (Jan 1999)	77°51'S 166°46'E (38)	Mid-slope on side of basalt scoria cone	Hypergelic Typic Anhyorthel
Marble Point (Jan 1999)	77°25'S 163°41'E (50)	Midslope of a gently sloping till/outwash surface	Hypergelic Calcic Anhyorthel
Bull Pass (Jan 1999)	77°31'S 161°52'E (152)	Colluvial fan of till material.	Hypergelic Nitric Anhyorthel

Results and discussion

Effects of Soil temperature on Hydra soil moisture probes

As the soil froze the θ_v-HP dropped to 0% (Figure 1). The θ_v-HP of the four soil cores remained constant for the approximately two days prior to freezing, and returned to similar moisture contents following removal from the freezer on day 6.

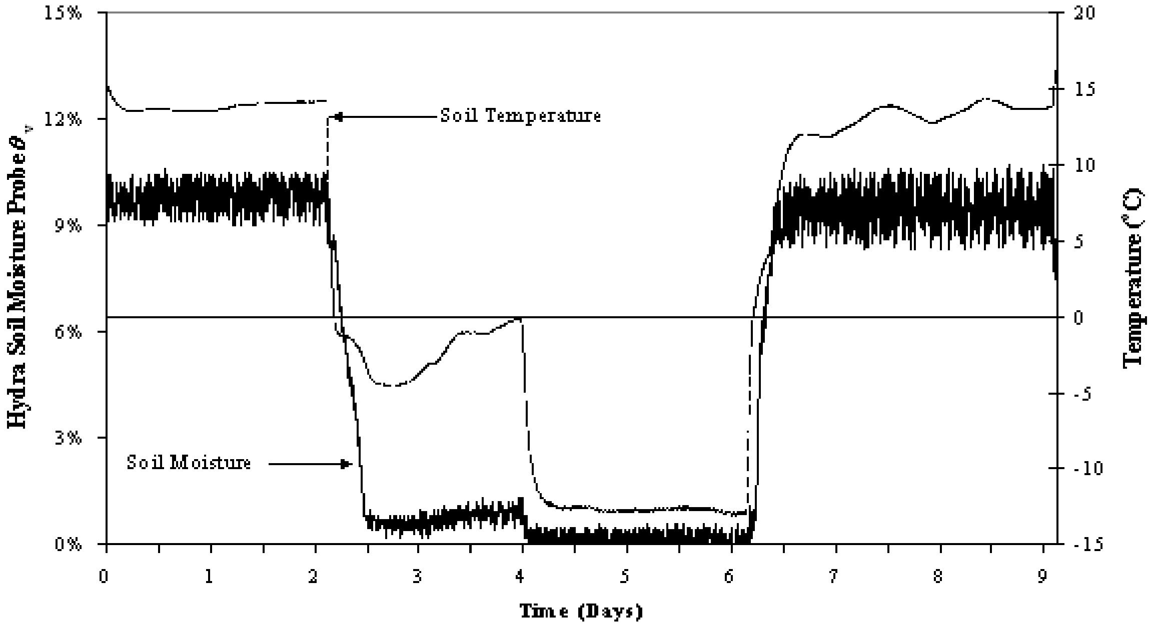

Figure 1. Example of soil moisture and temperature during and after freezing. (Gravimetrically determined θ_v was 11.8 % on day 0 and 11.3% on day 9.)

Direct measurements indicated that throughout the experiment there were no marked changes in soil moisture content in the cores. The decrease in θ_v-HP following freezing of the soil cores was attributed to the dielectric constant of the water decreasing to that of ice (i.e. $\varepsilon_{ice} = 3.2$ (Lide 1997/98)), and consequently causing the bulk dielectric constant of the soil to decrease.

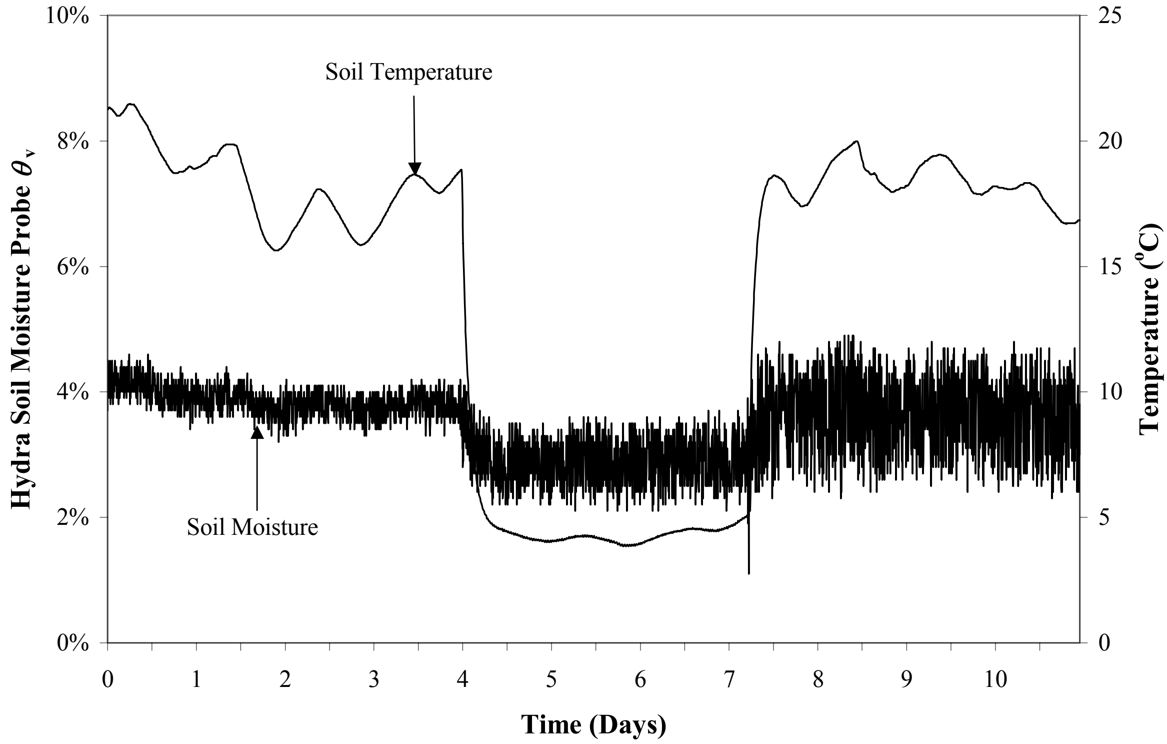

Figure 2. Example of Soil moisture and temperature before, during and after cooling from 17°C to 4°C. (Gravimetrically determined θ_v was 4.9 % on day 0 and 4.6% on day 12.)

An increase in "noise" in the probe measurements following warming was evident (figures 1 and 2). We do not have any explanation for this but in looking at data over longer time periods the level of "noise" remained consistent. The θ_v-HP also showed a temperature response over smaller air temperature changes (Figure 3). A 'loess' smoother (a smoothed trend line used to give an averaged θ_v-HP to eliminate the "noise" evident in the probe trace) fitted to soil moisture data gave a change in θ_v-HP of about 0.3% for a 4°C change in air temperature.

The Hydra soil moisture probes were also sensitive to temperature change when the soil remained unfrozen (Figure 2). With a temperature change from about 17°C to 4°C the θ_v-HP decreased from about 4% to 3 % and then recovered as the temperature rose again.

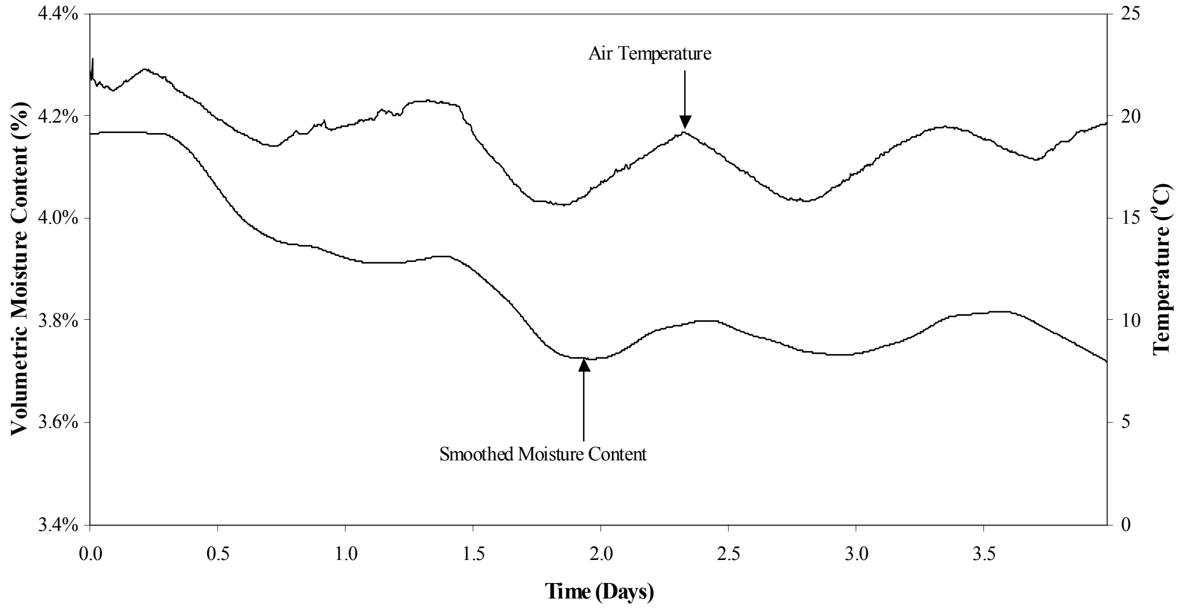

Figure 3. 'Loess' smoothed Hydra soil moisture probe measured volumetric soil moisture content and air temperature for a 4-day period. (Gravimetrically determined θ_v was 4.9 % on day 0.)

Effects of soil texture on Hydra soil moisture probes

When gravel was added to the sand, the Hydra soil moisture probes gave θ_v-HP readings that were lower than θ_v-GD by up to about 2% (Figure 4). For each of the gravel and sand mixtures, the relationship between the indirect Hydra soil moisture probe and direct measurements of volumetric soil moisture content showed a linear relationship with a slope of near 1, however, the offset between the two sets of measurements increased as the gravel content increased (Figure 4, Table 2).

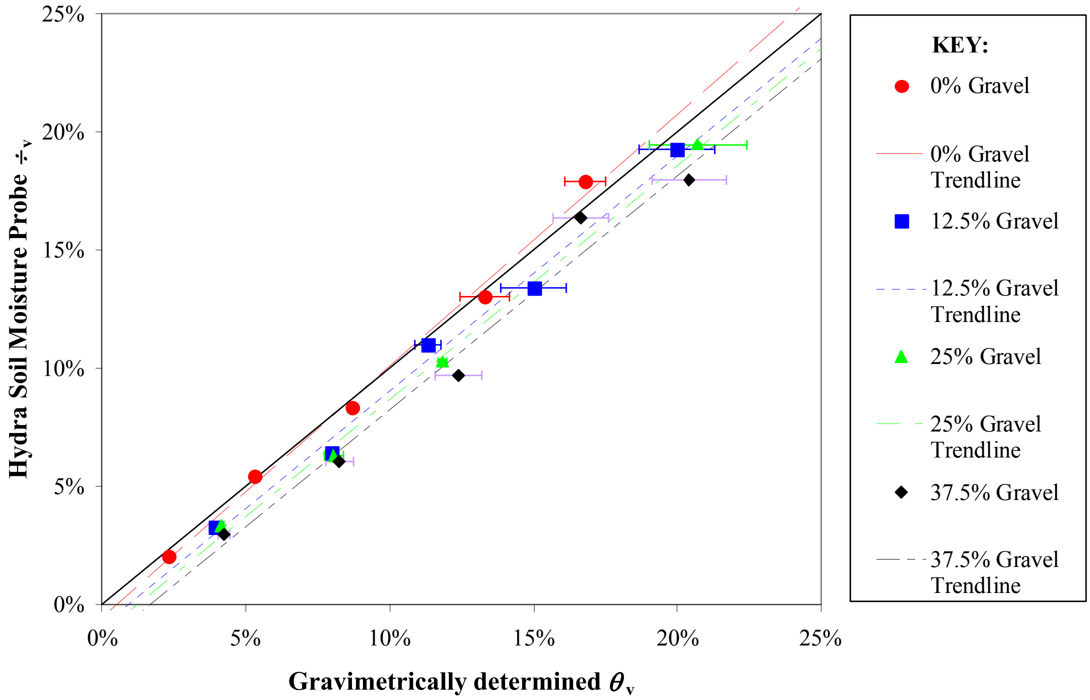

Figure 4. Relationship between θ_v-HP and θ_v-GD gravel contents between 0 and 37.5% in a sand soil.

Table 2. Linear regression analysis for the relationship θ_v-HP (y) and θ_v-GD (x) gravel contents between 0 and 37.5% in a sand soil.

Gravel / sand mix	Linear Regression Equation	r^2 value
0% gravel	y = 1.065x – 0.57	0.99
12.5 % gravel	y = 0.996x – 0.96	0.99
25% gravel	y = 0.990x – 1.24	0.99
37.5% gravel	y = 0.991x – 1.69	0.98

Effect of salt content on Hydra soil moisture probes

The three NaCl solutions (1% (0.17 mol L^{-1}), 2.5% (0.43 mol L^{-1}) and 5% (0.85 mol L^{-1})) when mixed with sand, gave electrical conductivities of between 0-500 µS cm^{-1} for the 1% NaCl samples, 400-1400 µS cm^{-1} for the 2.5% NaCl samples, and 400-2000 µS cm^{-1} for the 5% NaCl samples. The hydra probes tended to overestimate soil moisture content in saltier soils. When the soil moisture content was measured, the difference between θ_v-HP, and θ_v-GD was generally less than 5% for the 1% NaCl solution samples, while for the 2.5% and 5% NaCl solution samples, the difference was often up to and greater than 10%. For the soil samples with an electrical conductivity between 0 and 500 µS cm^{-1}, the difference between θ_v-HP and θ_v-GD was generally <5%. When the soil electrical conductivity was between 500 and 2 000 µS cm^{-1}, the difference increased to generally between 5 and 10%. Detailed data are included in Wall (2004). Soils of the Ross Sea Region of Antarctica predominantly have electrical conductivities <2 000 µS cm^{-1} (Claridge 1965; Bockheim 1979; Campbell 2000), however electrical conductivities of up to 8 000 µS cm^{-1} have been measured in the McMurdo Dry Valleys (Bockheim 1997; Campbell 2000).

Field verification of Hydra soil moisture probes

There was a near 1:1 linear relationship (r^2 = 0.85) between θ_v-HP and θ_v-GD measured in soils located near Scott Base (Figure 5). Most of the measurements were on soils with a volumetric moisture content of less than 20%, however, there were a few sites where snow-melt caused higher moisture contents (up to a θ_v-GD of 40%). The increased scatter observed in the field results was largely due to the large measurement error in the field determination of soil dry bulk density.

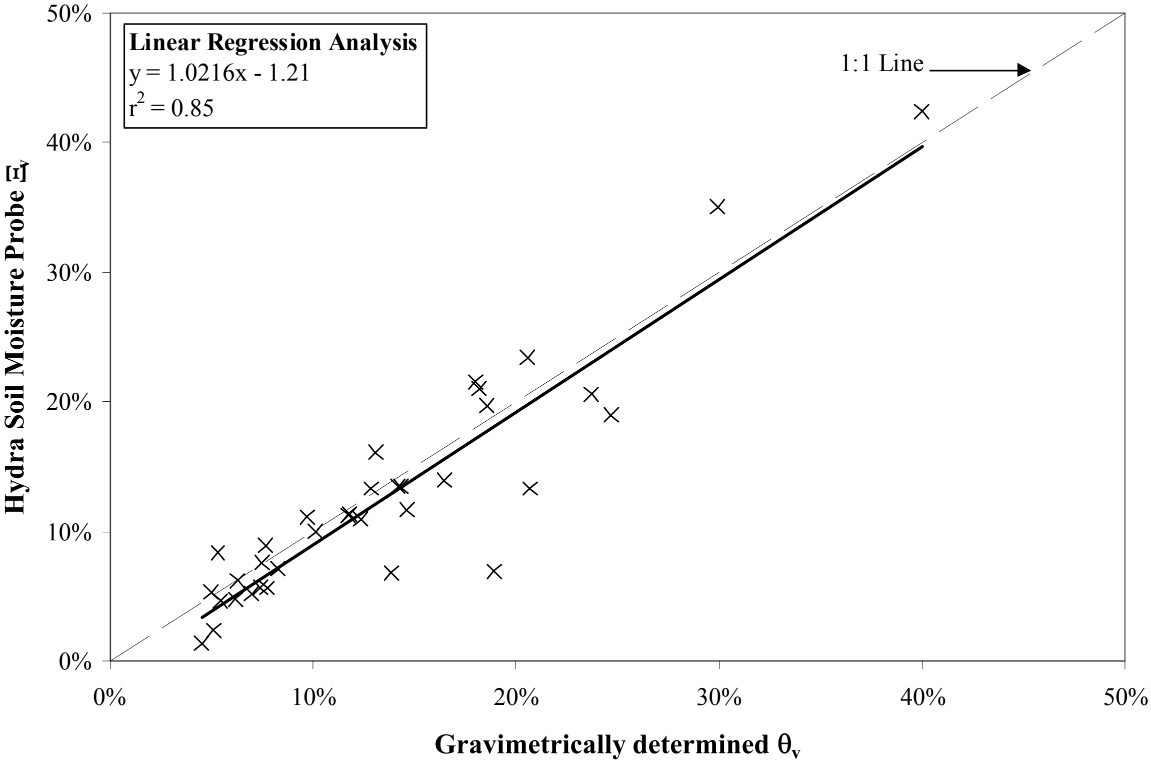

Figure 5. Field verification of Hydra soil moisture probes in soils near Scott Base.

Climate station soil moisture measurements

Soil moisture availability was limited at all three sites (Table 3). Scott Base and Marble Point have annual precipitation of about 200 mm water equivalent (New Zealand Meterological Service 1983) although not all of the precipitation reaches the soil as sublimation is prevalent. Scott Base had almost three times as many hours with a liquid soil moisture content of >5%, about twice as many soil-moistening events, and a lower maximum soil moisture content than Marble Point.

The soils of the Wright Valley are located in a dry environment with low precipitation (45 mm per year (Bockheim 1997)) and had a lower maximum liquid soil moisture content, fewer total hours with a liquid moisture content >5%, and fewer soil-moistening events than Scott Base or Marble Point (Table 3). Over the three summers only one soil-moistening event was observed in the Wright Valley in one of the two replicate Hydra soil moisture probes placed at the 2 cm depth, and moisture did not penetrate to the 20 cm depth.

Table 3. Mean soil moisture properties for Scott Base, Marble Point and the Wright Valley at the 2-5 cm soil depth, averaged over three summers (1999/2000, 2000/2001, and 2001/2002).

Location	Freeze/Thaw Events[1]	Total hours with liquid moisture content >5%	Number of soil-moistening events[2]	Maximum liquid soil moisture content
Scott Base	36	860	4	23%
Marble Point	52	310	2	32%
Wright Valley	79	1	0.3	5.4%

[1]Calculated by dividing the number of times the soil temperature crossed the 0°C line by 2

[2]Determined by distinct, rapid rise in soil moisture content of at least 3%, which were not due to freeze-thaw cycles. Data are mean number of events per year.

Freeze-thaw events were most common in the Wright Valley, and fewest at Scott Base (Table 3). In the Wright Valley, diurnal fluctuation in soil temperature, accentuated by shading by the Asgard Ranges for several hours per day, often caused the soil temperature to drop below 0°C. Scott Base and Marble Point generally had smaller diurnal soil temperature fluctuations than the Wright Valley, with diurnal freeze-thaw cycles more common at the beginning and end of the summer.

When soil-moistening events occurred, the soils took several days to dry (Figure 6).

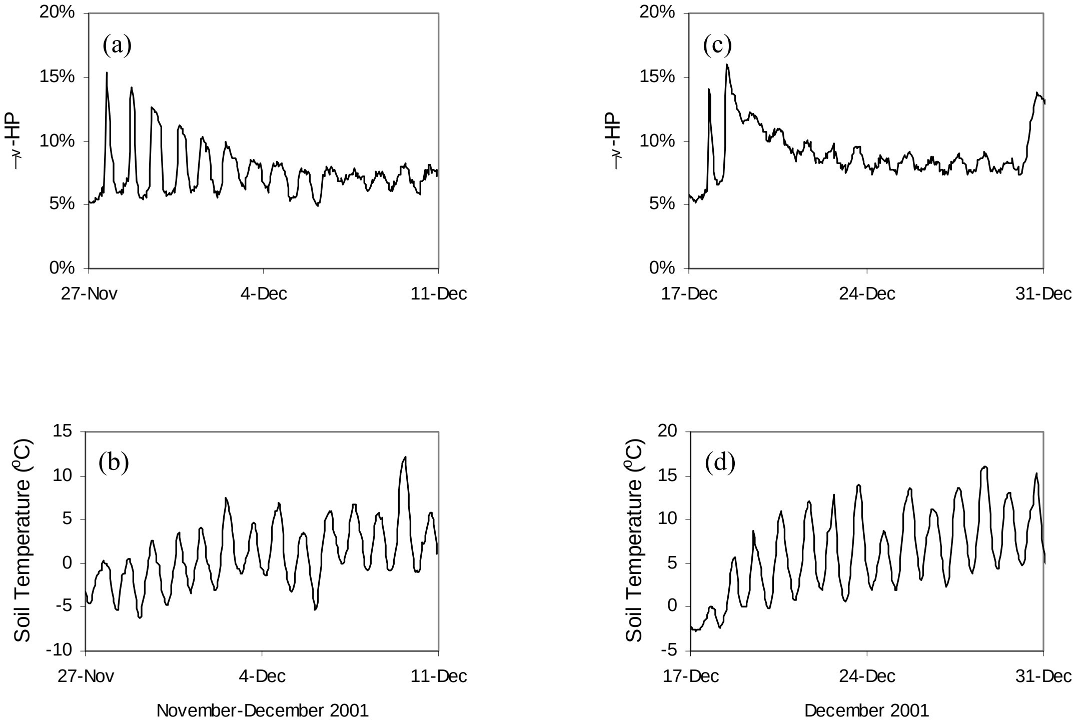

Figure 6. Drying period of soils at Scott Base with freeze-thaw processes operating (a & b) and with soil temperature constantly >0°C (c & d).

Soil-moistening events that occurred during periods when soil temperature was constantly above 0°C tended to take approximately 6 days to dry and return to pre-soil-moistening moisture contents (Figure 6). However, when freeze-thaw cycles were also occurring, the drying period of the near surface soils (2-5 cm) took approximately twice as long. The drying periods for both Scott Base and Marble Point were similar, while the only soil-moistening event recorded in the Wright Valley took approximately 7 days to dry. The soil-moistening event in the Wright Valley was smaller than either the Scott Base or Marble Point events, but freeze-thaw events were occurring during the drying period. The observed spatial variability at both Scott Base and Marble Point is such that there would be some areas with longer, or shorter, hours of moisture availability than those reported here. The longer period of moisture availability reported at Scott Base than Marble Point is likely to be due to the larger, steeper hillside on which the Scott Base climate station is situated, whereby there is more surface runoff as a result of snowmelt higher up the slope.

Conclusion

Hydra soil moisture probes are useful for determining the volumetric moisture content of Antarctic soils only when the soils are unfrozen. The Hydra soil moisture probes are sensitive to temperature with lower readings at cooler temperatures. The diurnal soil temperature range often experienced in the Antarctic summer would be expected to lead to variability in θ_v-HP of up to about 1%. The sensitivity to temperature is similar to that reported for other TDR-like probes (e.g. Yu *et al*. 1999; Pepin *et al*. 1995).

Soil texture influences the operation of the Hydra soil moisture probes. The gravel content of Antarctic soils can range from 0% to almost 100%. Hydra soil moisture probes used in gravely soils may underestimate the volumetric soil moisture content by up to about 2% for soils containing gravel contents of up to 37.5% (by weight). For soils that have a soil electrical conductivity of <2 000 µS cm^{-1}, the θ_v-HP may overestimate θ_v-GD by up to 5%. In soils with an electrical conductivity in excess of 2 000 µS cm^{-1} the Hydra-probe determination of moisture content may not be so reliable.

The cumulative effects of the soil temperature, texture, and salinity, on the volumetric soil moisture content measured by the Hydra soil moisture probes in Antarctic conditions are considered to have a limitation of ±3%, so long as the soils do not have an electrical conductivity over about 2 000 µS cm^{-1}. In field-testing, 80% of the data points fell within ±3% of the 1:1 line, where the possible sources for error were larger than in the laboratory testing. The limitation of ±3% moisture content reported here for Antarctic conditions is consistent with the accuracy claims of the manufacturer of the probe in regular operating conditions (Vitel Inc 1994).

The short periods where moisture is available are critical to both soil chemical and biological processes. Our data confirm the limited nature of moisture availability with the extreme case of the Wright Valley having only one, small, short-lived, discontinuous soil-moistening event in the three years of recorded data. Scott Base and Marble Point both have a few-hundred hours, over the course of a summer, in which soil moisture is available, thus providing limited opportunity for biological growth and other soil processes to proceed.

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