Estimations of moisture content in the active layer in an Arctic ecosystem by using ground-penetrating radar profiling

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Abstract

We applied high-frequency GPR at a study site in the high Arctic ecosystem of Northeast Greenland to evaluate its usefulness in assessing depth of, and water content in, the active layer at Zackenberg Valley (74°N; 20°W) to evaluate its usefulness in the high Arctic ecosystems. The study site includes different vegetation types, and it well represents of the entire valley, for which we aimed to determine the conditions and characteristics that influence the GPR performance in the active layer. The spatial distribution of moisture content along the transect studied was estimated using GPR data (400 MHz antenna), depth to permafrost, soil samples and vegetation observations. Vertical distribution of the water content in the unfrozen soil bulk was predicted for several points on the transect by combining data that influence the behavior of the radar waves with that of capacitive moisture probes. The statistical models resulted to be highly significant, thus assuming common conditions of the soil to the classified vegetation, we can obtain from the GPR data, truthful estimations of water content, and, moreover, we can predict the distribution to the bottom of the active layer. Hence, we conclude that GPR is a viable option for improving active layer spatial quantification of water contents that can be used to assess changes in the active layer in arctic regions.

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1. Introduction

Increasing spring and summer air temperatures is expected to affect the thickness of the active layer and permafrost regimes in the entire Arctic region (Hollesen et al., 2011; Osterkamp, 2005). They are also expected to have an effect on the regional energy balances, water availabilities and greenhouse gas emissions throughout the Arctic region (Dutta et al., 2006; Hinzman et al., 2003; Hollesen et al., 2011). Recent studies on the Arctic coastal plain (Brown and Romanovsky, 2008; Jorgenson et al., 2006) and more particularly in the active layer (Christiansen et al., 2008), show the vulnerability of permafrost areas to climatic variations. Changes in the active layer thickness and unfrozen yearly duration are directly linked to vegetation which is likely to be altered by the influences of snow distribution, length of the growing season and water balance. As a result, the depth of the active layer and changes in nutrient availability will alter the interactions between the soil and vegetation, and consequently affect the entire ecosystem (Klein et al., 2008; Walker et al., 2003). The active layer thickness is accordingly, one of the various important periglacial conditions that have been monitored with high frequency in the Arctic because it clearly indicates climate change. At Zackenberg lowland valley, in eastern Greenland the seasonal thaw of the active layer is observed in two sites of the “Circumpolar Active Layer Monitoring” program (CALM) (Brown et al., 2006; Christiansen et al., 2008), where measurements are traditionally conducted manually using a metal probe.

The conventional methods for monitoring active layer depth and water content can be enhanced by the use of ground-penetrating radar (GPR) which provides real-time, high-resolution and continuous images of the subsurface over wide areas. Due to the non-invasive nature of this geophysical technique, it has been widely used in varied geo-science applications, including mapping of frozen soil and permafrost characteristics (Annan and Davis, 1976; Arcone et al., 1998, 2006; Hinkel et al., 2001; Moorman et al., 2003). The high influence of moisture content (θ) in determining the measured relative dielectric permittivity (ε) of porous media allows GPR to be used in hydrological applications which have increased notably over the last decade (Slater and Comas, 2009). Different studies have already shown the effectiveness of using GPR for water content estimation in agricultural and lower-latitude soils (Grote et al., 2003, 2010; Huisman et al., 2003; Lunt et al., 2005).

GPR performance in soil sciences relies on the fact that soil components such as air, minerals, ice and water have contrasting permittivity values. In the active layer and frozen ground, permittivity values vary depending on the characteristics of the ground. For example, it

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has been determined to be in the range of 4.8 to 5.7 for alluvial permafrost and around 36 for the active layer (Arcone et al., 2003) whereas for liquid water it is 81. Water molecules in soil are differently bound to the mineral phase and each other, varying from tightly bound in hygroscopic water, ice or in very dry soil, which only contributes little to the total permittivity, to free water which contributes most to permittivity. Active layers may also retain some lenses of ice, while on the other hand frozen ground (i.e., with present temperature <0 °C) may not necessarily have all pores filled with solid ice, as air and unfrozen water may co-exist depending on water availability and salt concentrations (Hilhorst et al., 2001; Moorman et al., 2003).

Natural variability of materials due to freezing and thawing makes the active layer a complex soil for studies with GPR. GPR signal losses are relatively high due to the heterogeneity of the soil and the water content; therefore, there can be substantial variability in signal attenuation, dispersion and propagation velocity above 100 MHz (Arcone et al., 1998). Despite these possible drawbacks our previous results of water content estimations reveal that GPR is a potentially effective method in Arctic areas (Gacitúa et al., 2010).

Here we used GPR to estimate the spatial variation of water content of the active layer. The aim of this study was to develop a method that by including the variables that interact in the active layer, can be used for measuring the soil conditions in an efficient way. The Zackenberg area has been consistently studied (Meltofte et al., 2008) and hence provides advantageous scenery for the application of the method. Considering the range of thicknesses of the active layer in Zackenberg Valley, we used a fixed-offset 400 MHz antenna unit, which provides a good compensation between resolution and depth reached.

2. Materials and methods

2.1. Site description

Located in North-East Greenland (74°30 N, 20°30 W) (Fig. 1), the Zackenberg area is a high arctic valley system surrounded by mountains and underlined by continuous permafrost. The landscape is dominated by periglacial processes such as solifluxion. Changes in the ecosystem functioning because of predicted climate changes will likely occur at Zackenberg (Elberling et al., 2008) depending on the different plant communities and landscape types (with different soil formation dynamics). Vegetation is limited to a height of few centimeters and covers about 83% of the area below 300 m a.s.l., whereas the average active layer depth normally varies between 40 and 90 cm during spring/summer (Christiansen et al., 2008). However, an increment of 1 cm·yr⁻¹ in the maximum thawing of permafrost has been registered since 1996 (Hollesen et al., 2011). The study area’s parent material is dominated by non-calcareous sandy fluvial sediments and soils that are mostly cryoturbated with discontinuous horizons. The soil is slightly acidic to neutral, with pH generally increasing with depth (Elberling et al., 2008).

A 165 m representative transect was selected in the valley that included the major landforms, namely uphill, slope and valley bottom positions (Fig. 2). The spatial variation over small distances of the plant communities is influenced by micro topography, snow cover and hydrology. Five major plant communities in the Zackenberg valley are represented in the transect: Dryas heath, Cassiope tetragona heath, Salix arctica snowbed, Vaccinium uliginosum heath and grasslands (Elberling et al., 2008).

2.2. Calibration process

Periodic observations and GPR profiles were collected along the study line during August 2010, when the active layer was expected to have reached its maximum depth of up to 100 cm in the valley. Direct observations of depth to permafrost were carried out by inserting a steel rod at 1 m intervals throughout the transect to relate to the GPR measurements.

GPR profiling needs calibration for representative monitoring of soil moisture contents, which require a number of horizontal and vertical positioned instruments to obtain good coverage of an investigated area. Especially time-domain reflectometry (TDR) techniques have been used for estimating soil moisture (Galagedara et al., 2005;
Huisman et al., 2003; Robinson et al., 2008). To calibrate our GPR measured water contents along the transect, a total of 14 capacitive moisture probes operating at 100 MHz (PR4 Delta-T devices, UK), hereafter denoted MPs, were installed for measuring volumetric water content. Sites with different vegetation were selected to measure the volume water content of the soil at 10, 20, 30 and 40 cm below the surface. The sensors in the MPs are positioned to get one third of the cylindrical volume surrounding the probe, thus for one measurement the sensor is turned three times to cover the total soil volume.

The horizontal spatial distribution of the water content was estimated from the permittivity measured with the GPR and then calibrated using the MP data by a site-specific petrophysical relationship. More general petrophysical relationships (as per Roth et al., 1992; Topp et al., 1980) were used but no substantial improvement to the previous was obtained (Gacitúa et al., 2010). Sections were classified using vegetation information to restrict the areas to particular conditions of soil texture and water content because these limit the wave propagation velocity and the energy reflected from interfaces in the ground (Cassidy, 2009). Thereafter, we described the relationship of the reflected signal to the predominance of the vegetation distribution, which was quantified from high resolution photos of the ground. We estimated the percentage ground-cover for each vegetation type in squares of 20×20 cm² and then averaged to a lower resolution (Fig. 3). The vertical spatial distribution of water through the active layer was assessed by analyzing the signal wave characteristics from areas along the line where information of soil texture and MPs was obtained.

2.2.1. GPR data

A 400 MHz central frequency antenna unit (GSSI Inc.) and an 800 MHz antenna unit (Malå Geosciences) were dragged along the transect. Radar data collection was set continuous by which the antenna was dragged over the surface. Processing of the raw radar data included the horizontal resorting of traces to distance covered, removal of header gain used to provide better real-time interpretation in the field, correction of the surface arrival time and removal of the section in the radargram that exceeded the depth of interest.

Both frequencies were used during interpretation of the active layer bottom. However, electromagnetic waves are highly affected by soil heterogeneity that contains silt and clay, which characteristically have high rates of attenuation and loss as frequency increases (Davis and Annan, 1989). 800 MHz was only used in a preliminary data processing step as a reference to the 400 MHz data interpretation to corroborate uncertainties, and the acquired 800 MHz data are not discussed hereafter.

Travel time of the radar waves to the unfrozen/frozen interface was interpreted from the data (Fig. 4). The bottom reflection interpretation was done manually following the reflector from the frozen ground surface, guided by the direct depth measurements obtained using the metal probe every one meter throughout the transect. After correction of zero time and shifting of the radar profile, a possible error in the travel time interpretation of one pulse width of the signal was assumed due to the possible misinterpretation of the bottom reflector wave in some noisy sections in the radargram.

Travel time and depth were used to estimate velocity of the waves in the soil. The relative permittivity was obtained, as a first approach assuming low-loss conditions and low electrical conductivities by using an appropriate approximation [Eq. (1)] for high radar frequency in non saline geological materials (Davis and Annan, 1989). Velocity can then be expressed in terms of the real part of the permittivity (ε) and the velocity of the wave in the air (c = 3×10⁸ m·ns⁻¹), such that

\[ v = c/\varepsilon^{1/2} \text{[m/ns]} \]
To relate depth values to each trace, the discrete known depth measured using the steel rod in the active layer was linearly interpolated to the number of traces in the radargram. The slope of two consecutive known points gives the grade of possible deformation of the frozen soil in between. Considering uncertainties in the measurements on the field and the assumptions in the interpolation and calculations, propagation of error for each parameter was estimated.

2.2.2. Soil conditions and effect on GPR signal

Experimental studies have quantified the dependence between electromagnetic parameters of a media, the factors of losses and the frequency of radiation used (Knoll and Knight, 1994; Saarenketo, 1998). To include the soil condition in our analyses, we collected soil samples at 5 of the 14 MP calibration sites in 100 cm³ water-retention rings. Results of volumetric water contents were expressed on a 110 °C dried soil basis. Soil texture and organic carbon contents of composite samples (0–10, 10–20, 20–30, 30–40 and 40–50 cm depth intervals) were also obtained in the laboratory using respectively, the laser diffraction method and total combustion, to select the best manufacture calibration algorithms for the MPs.

The heterogeneity of the cryoturbated soils represents a drawback for GPR studies because there can be a substantial variability in signal attenuation, dispersion and propagation velocity especially at frequencies above 100 MHz (Arcone et al., 1998). The attenuation factor is thus a measure of the “lossiness” of the soil, which is greatly influenced by the electric properties of a material. Eq. (2) was used to estimate the attenuation factor ($\alpha$) for each site using the angular frequency ($\omega$) (the central frequency of the antenna), relative permittivity ($\varepsilon$) measured from radar data and the conductivity values ($\sigma$) obtained from tables (Davis and Annan, 1989) according to the texture composition percentage (gravel, sand, silt and clay) in each sample site.

$$\alpha = \omega \left( \frac{(\varepsilon / \sigma)^2}{1 + (\sigma / \sigma_0)^2} \right)^{1/2} - 1,$$

where $\omega = 2\pi f$ (frequency in Hertz), $\sigma$ is conductivity in S·m⁻¹, and $\sigma_0$ is permittivity of free space given as $8.8542 \times 10^{-12}$ F·m⁻¹.

In order to simulate the effect of attenuation in the reflected signal, the resulting attenuation factor was used to estimate a semi-theoretical decay curve of amplitude of the electromagnetic wave that propagates at a finite velocity at a determined distance from the source as $e^{-\alpha x}$ for each site.

The information contained in the received GPR traces was used to relate their behavior to the moisture measured using MPs at the five calibration sites for which we calculated attenuation and losses from soil samples (Fig. 5). From the original radargram we obtained the instantaneous amplitude (envelope of the signal), which is a measure of the reflectivity strength (Arcone et al., 2003). This amplitude is proportional to the square root of the complete energy of the signal at an instant in time, which gives an overview of the energy distribution. The envelope was obtained for the section of traces at five sites where we physically sampled the soil. Representative traces were produced from the averaged sections (20 scans) for each site. The amplitude of the envelope for each reference trace was normalized by dividing the amplitude of each sample point by the mean amplitude for the section of the trace that corresponds to the active layer thickness (max. 324 samples). The normalized amplitude of the trace was then multiplied by the corresponding attenuation curve. After applying the respective attenuation curve to the length of the reflected energy profile we used linear models to relate them to the measured water content at different depths.

2.2.3. Statistical analyses

The statistical software R (version 2.12.1) was used to assess the relationships developed including simple linear regression to more complex multiple linear regression and linear mixed effect model tools. The evaluation of the relationships requires the statistical significance (p values) to be lower than 0.05.

In order to test whether soil moisture contents measured with the two methods were comparable, we applied a linear mixed-effect model (LMEM). Sampling method and depth (statistically named as continuous variable) together with their interaction were included as fixed explanatory variables and site was defined as a random variable. The 14 MPs along the transect were used with the radar data to obtain a simple linear model between moisture content and permittivity determined from GPR reflection travel times. Our first approach was based on the strong dependence of the soil permittivity on water. The averaged volumetric water content across the measurements at the four MP depths was compared to the permittivity values obtained from wave velocity [Eq. (1)]. Based on a simple linear regression, water content can be expressed in the following equation, which we call Model 1:

$$\theta = 9.595 + 0.823e,$$

where $\theta$ is the water content (vol.%), expressed as a simple linear regression, but with a poor $R^2 = 0.44$. However, moisture content variability is affected by the interactions of other factors, such as spatial distribution of vegetation, soil texture, soil depth, and topography among others. Thus, we developed a second, more advanced generalized linear model as a function of the permittivity, vegetation cover and depth of the layer ($d$).
is expressed in Eq. (4) as:

\[ \theta = 39.154 + 18.239 \rho_1 + 27.322 \rho_2 + 7.267 \rho_3 - 52.241 d. \]  

Hence, Model 2 for moisture content based on the soils show any evidence of autocorrelation between the components. In addition, residuals for Model 2 were normal, stochastic and did not indicate any correlation between the components.

3. Results

3.1. Moisture content: MPs vs. retention rings

The results of the test showed that in general, no significant difference in soil moisture was found between the two methods (p = 0.26) and a general significant increasing with depth (p < 0.01). However, the interaction term between method and depth was significant (p < 0.001) meaning that the relationship between soil moisture and depth differed between the two methods. As the two methods differed in their relationship of soil moisture no simple convention factor can be made. In the following analyses MPs soil moisture data are used as representative unbiased estimates of the water content in the unfrozen soil, because the statistical analysis suggested that the most likely cause of the discrepancy at single points was the soil water heterogeneity.

3.2. Horizontal moisture content from GPR

The results of multiple regression showed that there is an influence on water content from vegetation types. Vegetation can be classified into grassland (including moss and herbs), woody shrubs (Dryas heath, C. tetragona heath, S. arctica snowbed, V. uliginosum heath), and a third condition that corresponds to the dry and sparsely vegetated areas. Therefore, the total proportional presence of grassland (\( \rho_1 \)), heaths (\( \rho_2 \)), fell field (\( \rho_3 \)) and depth (d) were found to significantly improve the model (\( R^2 = 0.74, p = 0.001 \)) and offer the best compromise between number of variables and statistic coefficients. Furthermore, residuals for Model 2 were normal, stochastic and did not show any evidence of autocorrelation between the components. Hence, Model 2 for moisture content based on the field measurements is expressed in Eq. (4) as:

\[ \theta = 39.154 + 18.239 \rho_1 + 27.322 \rho_2 + 7.267 \rho_3 - 52.241 d. \]  

Depth of the active layer is fundamental for the estimations of permittivity. Estimations of water content are therefore best validated after 75 m in the transect, where the bottom of the active layer was clearly detected. Here the error in the permittivity for each trace was estimated to be less than 3% in average.

From 100 to 165 m a clear reflector is observed that indicates liquid water filled pore on top of the frozen ground which appears as a clear reflector in the radargram. Clearly Model 1 is less robust for matching trends to the MP data than is Model 2, where all the predictions produced for volumetric water content are constrained to realistic values (Fig. 6-B). However, this approach does assume that there is homogeneity in the soil and that the soil moisture conditions in the upper 40 cm (where MP data are available) represent the entire active layer.

3.3. Vertical distribution of moisture

Fig. 7 shows the results of the linear mixed models for the different relationships representing the levels of attenuation introduced as a consequence of the soil conditions (from data in Fig. 5). Here the vertical soil moisture distribution in the entire active layer bulk was predicted. The curves show the distribution of moisture content as a result of the relationship between MP measurements and the strength of the signal reflected from the bottom of the active layer. The resulting predicted curves for sites P4–P9 and P12, appear statistically highly significant (p < 0.01).

4. Discussion

MPs detect the soil moisture by the TDR technique measuring the response of the sensors to permittivity approximately 10 cm radio. Water content from the soil extracted in retention rings is a very accurate way to measure the real volume water content but represent only point measurements (c. 100 cm³) at time of sampling. Both methods were combined at 5 calibration sites (out of the 14 locations with MP instruments), in which for most cases MP data suggested a higher volumetric content of water than the sampling methods used. This discrepancy could be caused by factors such as poor calibration of MPs, the timing of measurements, and displacement. Additional

effects directly related to soil water content, which in turns affect the
electric properties of the soil, could be microbial processes in areas
with permanent high saturation (Atekwana et al., 2006).

In results for the application of both Model 1 [Eq. (3)] and Model 2
[Eq. (4)] showed in Fig. 6-B, Model 2 seems to provide a quite stable
curve of variability of the moisture content for the majority of the
transect. However, results obtained in the section between 45 and
75 m cannot be validated. This is due to the high variability in the ac-
tive layer depth here, which appears to result from the coincidence of
the topographical joint of the slope and the plain valley that is crossed
by the transect (footslope position) where snow is accumulated for a
longer period than for more exposed areas (Fig. 2). Here the linear in-
terpolation of known depths in the footslope position from 45 to 75 m
yields an uncertainty up to about 30 cm which corresponds to 50% of
the depth used in the calculations. Additionally, as it is seen in the
radargram (Fig. 4), the active layer bottom here is rougher; therefore,
the active layer interpretation becomes more difficult, resulting in
additional uncertainty that further affects the soil water estimations.
This is clearly explained in results obtained for permittivity values
(higher than 80) in Fig. 6-A for this section, that yield in wrong
water estimation using Model 1 (above 100%).

In Fig. 4 there is an increment of the strength in the reflection after
100 m, this corresponds to the lowland (Fig. 2) where water is
retained after it runs off from higher elevations. Here the presence of
capillary-retained water is expected to increase with depth. This is
well represented in Fig. 7 where the relation between the energy
reflected, dissipated or lost yields in curves that show higher satura-
tion (P9 and P14). Particularly in P14, the water content curve

![Fig. 6. Variation of horizontal moisture distribution. A) Estimated dielectric permittivity from radar data. B) Comparison between predictions for moisture content using both models 1 and 2, and averaged soil moisture probes (MP) measurements. Gray ranges represent the carried uncertainty of parameters derived from the field measurements.](image)

![Fig. 7. Vertical water distribution. Vertical distribution of moisture in the active layer for sites P4, P7, P9, P12 and P14 respectively. Curves obtained from the relationship of the attenuated reflected signal and the moisture measured by soil moisture probes (MP) at 4 depths at the five reference sites.](image)

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markedly increased and we obtained 80% water at 51 cm depth, while the maximum depth is 57 cm. We assume these 6 cm of active layer on top of the frozen ground are highly saturated (up to 100%). Less accuracy in the fitted curve was obtained at sites P7 and P14 compared to curves for P4, P9 and P12; which is likely caused by the heterogeneity of the soil. Nevertheless, all of them follow the trend of the distribution of moisture content down to the bottom of the active layer according to the discrete measurements.

The resulting semi empirical relationships between water content and calculated permeability are subject to unavoidable errors resulting from the necessary assumption that the soil is homogeneous and that interpretation can become subjective where soil conditions are particularly inhomogeneous and the frozen/unfrozen interface is not smooth. Nevertheless, our results show that GPR can successfully estimate continuity and soil moisture variability of the active layer by characterizing the soil with the factors that intervene in the active layer processes.

5. Conclusions

The fundamental principles of electromagnetic behavior from GPR data were used to obtain continuous representation of the spatial variation of moisture content in the active layer through a representative transect. GPR was further able to detect the continuity of the active layer bottom. The measured permeability was complemented to vegetation cover information and depth of the layer to estimate water content. At the same time we have proven that by relating changes in the signal received to soil properties we can accurately estimate the vertical distribution of the moisture content in the active layer.

Collection of data using continuous profiles, fixed-offset ground penetrating radar is fast and it can provide continuous information of large areas without disturbing the soil and vegetation. This constitutes a different method from those regularly used for monitoring the active layer (Christiansen et al., 2008). We therefore see GPR as a valid method to estimate water content in the cryoturbated soil, because it provides a reasonable compromise between effort and efficiency of the results for its use in larger ecosystem observation sites such as the Zackenberg valley, NE Greenland.

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References

Arcone, S.A., Peapplesz, P.R., Liu, L., 2003. Propagation of a ground-penetrating radar and Geodynamics (ZAMG) of Austria who kindly supported

Citterio from the Geological Survey of Denmark and Greenland

Arcone, S.A., Finnegan, D.C., Liu, L., 2006. Target interaction with stratigraphy beneath

Arcone, S.A., Peapplesz, P.R., Liu, L., 2003. Propagation of a ground-penetrating radar and Geodynamics (ZAMG) of Austria who kindly supported


