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Direct current (DC) resistivity and induced polarization (IP) monitoring of active layer dynamics at high temporal resolution

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ABSTRACT

With permafrost thawing and changes in active layer dynamics induced by climate change, interactions between biogeochemical and thermal processes in the ground are of great importance. Here, active layer dynamics have been monitored using direct current (DC) resistivity and induced polarization (IP) measurements at high temporal resolution and at a relatively large scale at a heath tundra site on Disko Island on the west coast of Greenland (69°N). At the field site, the active layer is disconnected from the deeper permafrost, due to isothermal springs in the region. Borehole sediment characteristics and subsurface temperatures supplemented the DC-IP measurements. A time-lapse DC-IP monitoring system has been acquiring at least six datasets per day on a 42-electrode profile with 0.5 m electrode spacing since July 2013. Remote control of the data acquisition system enables interactive adaptation of the measurement schedule, which is critically important to acquire data in the winter months, where extremely high contact resistances increase the demands on the resistivity meter. Data acquired during the freezing period of October 2013 to February 2014 clearly image the soil freezing as a strong increase in resistivity. While the freezing horizon generally moves deeper with time, some variations in the freezing depth are observed along the profile. Comparison with depth-specific soil temperature indicates an exponential relationship between resistivity and below-freezing temperature. Time-lapse inversions of the full-decay IP data indicate a decrease of normalized chargeability with freezing of the ground, which is the result of a decrease in the total unfrozen water and of the higher ion concentration in the pore-water. We conclude that DC-IP time-lapse measurements can non-intrusively and reliably image freezing patterns and their lateral variation on a 10–100 m scale that is difficult to sample by point measurements. In combination with laboratory experiments, the different patterns in resistivity and chargeability changes will enable the disentanglement of processes (e.g., fluid migration and freezing, advective and diffusive heat transport) occurring during freezing of the ground. The technology can be expanded to three dimensions and also to larger scale.

1. Introduction

Twenty-five percent of the Earth's land area is underlain by permafrost, which has been frozen for at least two consecutive years (Anisimov and Nelson, 1996). The active layer covering the permafrost thaws every year and has increased in thickness over large tracts of the Arctic (Mishra and Riley, 2014) due to climate change. Cold temperatures and long cold-seasons in the Arctic keep nutrient availabilities and thereby primary production low. However, there is an increasing interest in the active layer processes as easily available forms of carbon and nitrogen are being released upon stimulated microbial decomposition of soil organic matter in the Arctic (Wild et al., 2014). This will play a critical role for the release of greenhouse gases (Hayes et al., 2014), and it will affect the timing of nutrient availability for plants upon springtime when the active layer thaws from above. In this way the active layer dynamics control both the potential carbon release measured as decomposition of organic matter, but also the C sink strength of the Arctic biosphere measured as increasing nutrient availability and plant growth (Hollesen et al., 2011).

Freeze–thaw dynamics within the active layer and top permafrost are closely linked to the availability of water and salt in the ground, which influence the freezing point depression and ions (nutrient) translocation in the profile. However, despite the importance of high-resolution data on active layer and top permafrost dynamics, data are limited due to difficulties associated with repeated non-destructive sampling of the active layer under in-situ conditions during the critical time periods of freezing and thawing. Temperature and other depth-

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resolved information such as soil moisture are typically restricted to few point locations and are hard to extend to a larger scale.

Geophysical measurements can image permafrost and the active layer at a larger scale of tens to hundreds of meters. For example, Hubbard et al. (2013a) combine LiDAR and geophysical datasets in a cluster analysis to detect zones with different geomorphic, hydrological, thermal and geochemical properties. Gangodagamage et al. (2014) calibrate satellite data with ground truth and are able to predict both small and larger scale variations in active layer thickness across an area of 300 × 500 m. Electrical properties of the shallow subsurface at the scale of a few hundred meters can be sensed by electromagnetic induction data, and Dafflon et al. (2013) have shown their potential for active layer mapping.

While these LiDAR, satellite and electromagnetic induction data are able to cover large areas, they are not suited for continuous monitoring of active layer dynamics, because they cannot provide continuous measurement time-series. Methods that use permanent installations such as electrical resistance tomography with buried electrodes are better suited for this purpose, and they yield a relatively high spatial and temporal resolution. Time-lapse inversion of repeated direct current (DC) measurements allows both active layer dynamics and interannual permafrost conditions to be delineated vertically as well as laterally, where especially the lateral variations are difficult to obtain from drillings alone. Hauck (2002) introduced DC resistivity for monitoring of alpine permafrost and showed that variations in electrical resistivity can be used to determine the freezing depth. Analyses of a comprehensive DC resistivity monitoring dataset from a 7-year study at Schilthorn, Swiss Alps (Hilbich et al., 2008, 2011) have proven the applicability of DC for monitoring of freezing and thawing processes on short-term, seasonal, and long-term scales. The DC resistivity monitoring examples of alpine permafrost also include hard rock targets (Krautblatter and Hauck, 2007; Krautblatter et al., 2010), which require special electrode design and instrument settings, such as using high voltages, because even the thawed rocks have resistivities larger than 10 kΩm and current injection is very difficult. To our knowledge, in contrast to high altitude permafrost, no example of DC resistivity monitoring examples exists of Arctic permafrost.

The electrical resistivity of sediments and rocks is a function of porosity, water content, pore-water ion concentration, temperature and surface conductivity. Freezing of the rocks increases the electrical resistivity by transforming the electrical conductor water into the insulator ice. In unconsolidated sediments, there is typically an exponential increase of resistivity below 0°C temperature (Hoekstra et al., 1975), while a linear relationship has been reported for hard rock (Krautblatter et al., 2010). However, due to the other factors influencing resistivity, the inverted resistivity cannot be transformed directly into temperature, especially when changes in water saturation might happen simultaneously to freezing.

Measurements of induced polarization (IP) are sensitive to the grain surface to pore volume ratio and the grain surface charge (e.g., Lesmes and Frye, 2001; Slater and Lesmes, 2002) and can therefore help to image the different processes associated with freezing of sediments. IP monitoring has been used in field studies to image changes in geochemistry associated with bio-stimulation (Flores Orozco et al., 2011; Johnson et al., 2010; Williams et al., 2009) and CO_2 injection (Doetsch et al., 2015) in shallow aquifers, but no field study related to permafrost is known to us.

Wu et al. (2013) conducted laboratory column experiments to explore the potential of the frequency-domain complex resistivity method for monitoring the freeze–thaw transitions of the Arctic permafrost soils. Over two orders of magnitude of resistivity variations were observed when the temperature was increased or decreased between -20 and 0 °C, and smaller resistivity variations were also observed during the isothermal thawing or freezing processes that occurred near 0 °C. The IP phase response was found to be related to the unfrozen water in the soil matrix, and a shift of the observed spectral response to lower frequency was observed during the isothermal thawing process, indicating a sequential thawing of fine particles within the soil matrix first and coarse particles thawing at later times. Laboratory measurements of Kemna et al. (2014) also indicate that some of the polarization mechanisms break down upon ice crystallization, decreasing the IP effect, in accordance with results of Wu et al. (2013).

The aim of this study is to demonstrate the use of DC and IP monitoring to quantify thaw–freeze dynamics at a High Arctic site in Greenland. We hypothesize that combined DC-IP measurements are able to capture hourly to daily variations in the electrical resistivity and thereby improve future assessment of temporal and spatial changes in water content and pore-water ion concentrations associated with freeze–thaw cycles in nature. For this purpose, we perform time-lapse DC and IP measurements of the ground during freezing in fall and winter (2013–2014) and test how combined DC-IP measurements improve the understanding of the processes occurring during freezing of the ground. To our knowledge this is the first reported field study of IP active-layer monitoring and the first DC monitoring study of Arctic permafrost and active layer at a relatively large spatial scale.

2. Field site

2.1. Field site characterization

The study site (N69°15′, W53°30′, 30 m a.s.l.) is an *Empetrum nigrum* and *Betula nana* heath tundra near the Arctic Station on Qeqertarsuaq/ Disko Island on the west coast of Greenland (Fig. 1b). The island is

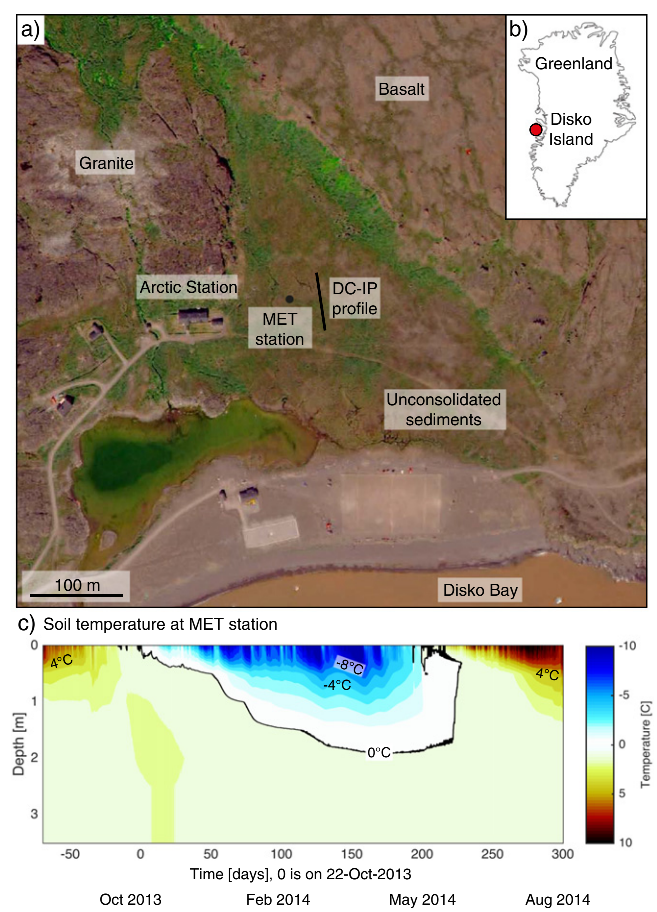

Fig. 1. General site information with an aerial photo of the field site on Disko Island in (a), its location in western Greenland in (b) and soil temperatures in (c). The DC-IP profile is installed on unconsolidated sediments at ~33 m elevation and the soil temperatures measured at the weather station (c) show temperature variation to a depth of approximately 2 m.