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Time-lapse electrical resistivity tomography for improved characterization of thaw-sensitive permafrost

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Motivation

Fine-grained permafrost sediments, sometimes with varying level of salinity in the pore water, complicate infrastructure design and maintenance in the coastal regions of Greenland. In spite of ground temperatures well below 0 °C, these sediments may exhibit mechanical properties like thawed soils. Locating and characterizing such sediments in remote areas of planned infrastructure development is a logistically and financially extremely demanding task. High cost of drilling and site investigation campaigns often prevent gaining deeper knowledge about ground conditions.
In this work (Tomaskovicova, 2017), we developed and tested an innovative approach to mapping and describing permafrost sediments. We used time-lapse electrical resistivity soundings collected from the ground surface in connection with ground surface temperatures and numerical modelling to provide an indication about the ground thermal state, depth of annual thaw and freezing point depression. Among the main advantages are reduced logistical and financial burden, better understanding of in-situ processes and soil characteristics and reduced environmental impact of the non-invasive surface method.

Approach

The coupled modelling framework allows inferring ground thermal conditions from changes in electrical response. The electrical resistivity tomography (ERT) is a method that maps electrical properties of a section of the subsurface located below the investigated profile. The method is very sensitive to phase change between water (low resistivity, typical for thawed soil) and ice (high resistivity, typical for the frozen portion of the ground) at sub-zero temperatures.
The approach to recovering ground thermal properties from geoelectrical data is illustrated on Figure 1 and detailed in the following:
The coupled model consists of two, essentially standalone, modules: a heat transfer model and an electrical resistivity model. The 1D heat conduction model calculates the temperature distribution in the subsurface given a set of initial and boundary conditions, forcing ground surface temperatures and thermal parameters. The calculated temperature distribution is translated into a 1D multi-layer geoelectrical model. This is done by dividing the model into many equally spaced layers. For each layer of the resistivity model, the layer-representative temperature is found by interpolating between the nearest grid points of the heat model. For each layer-representative temperature, fractions of water, ice and rock are found using a relation describing unfrozen water content in soils at subfreezing temperatures (Lovell, 1957). The effective bulk soil resistivity for the given model layer is calculated from specific resistivities of the respective ground constituents using a resistivity mixing rule. From the geoelectrical model, the forward apparent resistivity response is calculated by the CR1Dmod program (Ingeman-Nielsen & Baumgartner, 2006) using the same electrode configurations as on the field site. The calculated apparent resistivities are then compared to the field geoelectrical measurements. The difference is minimized by adjusting both the thermal parameters of the heat model and specific resistivities of the resistivity model from which the forward resistivities are calculated. The final heat model calibration is validated by comparing the simulated ground temperature distribution to a borehole temperature timeseries from the location of the time-lapse ERT acquisitions.

A monitoring station for automated measurement of ground resistivity was built near the airport in Ilulissat, West Greenland. The station has been acquiring daily ground resistivity soundings and surface temperatures for development of the model, and ground temperature in three boreholes for model validation.
Our modelling work showed that the resistivity-calibrated heat model reproduces field-measured ground temperatures with an accuracy (±0.55 °C) comparable to a traditional calibration on based directly on measured borehole temperatures. The timeseries of resistivity data are indicative of soil freezing/thawing characteristics, such as the freezing point depression and different rate of freezing/thawing.

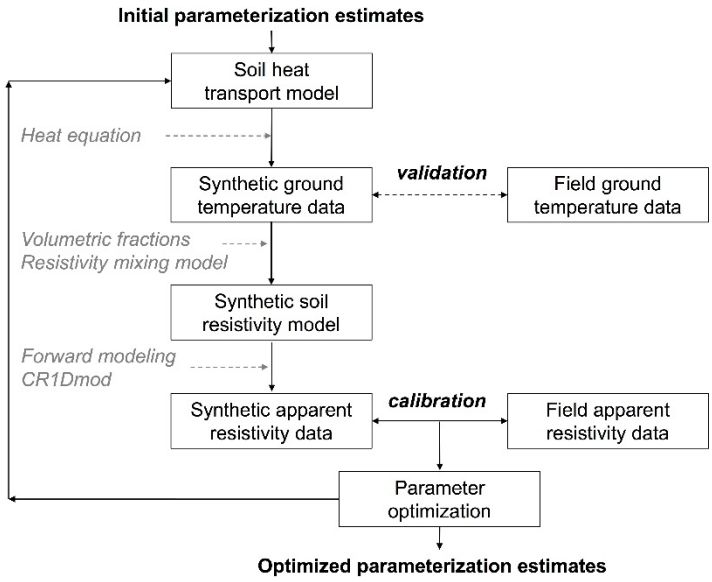

Figure 1: Scheme of the coupled inversion approach.

Conclusions

The calibrated coupled thermo-geophysical model can be exploited for predictions regarding the ground thermal regime following various surface temperature scenarios. For example, a climate change scenario can be applied to estimate a change in annual thaw depth. The model could therefore be used as an indicative tool when designing infrastructure and foundations in permafrost-affected areas.
The main advantages of the method are that it allows to describe the effective freezing/thawing point of the ground (which may be <0 °C), it allows to obtain 2-3D information about soil properties and it is logistically and financially comparatively less demanding than traditional investigation methods (drilling and borehole temperature measurements). The trade-off is securing the permanent power supply for the duration of the measurements.

References

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