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Permafrost degradation risk zone assessment using simulation models

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Abstract

Climate change is detrimental to permafrost and related processes, from hydrological and ecological to societal. We present the current and future state of permafrost in Greenland as modeled numerically with the GIPL model driven by HIRHAM climate projections till 2075. In this paper we developed the Permafrost Thaw Potential (PTP). This is the potential active layer increase due to climate warming and surface alterations. PTP was used in a simple risk assessment procedure usefull for engineerings. Climate warming will result in wide-spread permafrost warming and degradation. Construction on sedimentary deposits with permafrost should be avoided south of latitude 67.

1 Introduction

Tourism in Greenland has in recent years increased and has put more stress on infrastructure. Construction and expansion of airstrips, roads and facilities to accommodate increased travel to and within Greenland requires a risk assessment of permafrost dynamics in the affected areas especially in conjunction with predicted climate warming (IPCC, 2001, 2007; ACIA, 2004). In West Greenland most villages and cities from the 18th and 19th century are located in natural bays with gentle relief that provide a good harbor and the opportunity to construct houses making use of bedrock exposure for a stable foundation. However, population and tourism pressure and the increasing need for infrastructure forces construction onto more challenging ground with deeper non-consolidated sediments and ice rich permafrost.

Most of western Greenland is uplifted during glacial rebound (Weidick, 1976); which exposed marine sediment filled depressions to a cold climate. The sedimentary deposits are often poorly drained, but over thousands of years precipitation has washed out the salts from the sedimentary column (Foged, 1979). The soils in these depressions have also developed a small organic horizon near the surface that promotes

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permafrost growth. Ice rich permafrost formed in the upper washed out portion of the sediment pockets, and is protected from summer heat by vegetation and organic material.

Previous estimation of permafrost distribution were based mainly on air temperature observations and simulations (Christiansen and Humlum, 2000). The spatial distribution of the observations is very limited and, in addition, the landscape is not conducive to interpolation of climate data over larger distances, due to steep topography and coastal effects. Engineers need more detailed information to assess the cost of infrastructure improvements and development. Detailed information on spatial distribution of soil temperatures was till now not available in the ice free terrestrial portion of Greenland. We have created a dataset that provides soil temperature and active layer depth data at a 25 km resolution, which can be used for risk assessment of projects on that scale. The data set includes both bedrock (warmer ground) and sediment (cooler ground) calculated temperature and active layer depth, which provides a range of ground conditions using the same climate projection as a driver.

The current risk assessment strategy is complex in its decision scheme or at resolutions to big for engineering purposes (Nelson et al., 2001). To simplify and downscale this procedure we propose to apply the results from our spatially distributed permafrost model to estimate the regional risk of permafrost degradation over terrestrial Greenland.

In this paper we present the results of regional permafrost simulations for Greenland. We propose a new simplified risk zonation procedure for permafrost degradation based on substrate, ice content and the regional permafrost thaw potential. As an example of the impact on community level, we will discuss the application of our risk assessment strategy for the towns of Ilulissat and Sisimiut, West Greenland.

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2 Regional permafrost modeling

During the last 20 yr, many permafrost models have been proposed with a variety of applications (Stendel and Christensen, 2002; Romanovsky et al., 2002; Nelson and Outcalt, 1987; Christensen and Kuhry, 2000; Sazonova and Romanovsky, 2003; Anisimov et al., 2002; Riseborough et al., 2008). We used in our study a numerical simulation model called GIPL 2.1, a parallelized version of GIPL 2.0 (Tipenko and Romanovsky, 2001; Sergeev et al., 2003) for simulating spatially distributed ground temperatures over the ice free part of Greenland. GIPL 2.1 is a state of the art parallelized numerical model which takes a temperature-depended latent heat effect into account (Marchenko et al., 2008).

Complex topography and coast line configuration are key characteristics of Greenland. This requires high resolution simulation of climate as well as permafrost distribution. A good estimate for air temperature is acquired through the application of a high resolution regional climate model (RCM) HIRHAM 4.0 with a grid cell size of 25 by 25 km. This climate model data set of the A1B scenario, which covers the entire Greenland domain, is available for the period 1950 to 2080 (Stendel et al., 2008a). The modeling domain layout used in the GIPL permafrost model is identical to that of the driving RCM, but covers only the ice-free land areas. To generate the range of ground temperature solution we generated two datasets for this domain: a warmer dataset which we will call the bedrock dataset and a colder dataset, which we call a sediment dataset. Both datasets were developed for the same area and driven by the same air temperature.

Permafrost in Greenland is dominated by areas of bedrock with pockets of sediments often covered with a layer of organic material. Due to the vastly different thermal properties of the bedrock compared with the sedimentary basins we chose to split the simulation in two categories: the bedrock simulations and sediment simulations. As noted above the bedrock run is a warmer model run where all cells have bedrock properties. In the colder run of the GIPL model all grid nodes have sediment properties.

The difference between the runs is caused by the presence of a greater thermal offset in the case of the sediment run (Romanovsky and Osterkamp, 1995). The thermal offset is the result of thermal conductivity differences between frozen and thawed porous media. The other difference between the permafrost model runs is the reduced porosity of the ground which results in a reduced production/consumption of latent heat for the bedrock simulation. The lack of liquid water and ice results effectively in faster and deeper warming during the summer, however also faster and deeper cooling in the winter, but compared with the sediment simulation, with more ice or water resulting in slower changes in temperature around the melting point, there is a difference in winter and summer energy transfer rate due to the larger amount of ice or water.

The thermal properties for our sediment run are given in Table 1. The table contains: the moisture content, unfrozen water characteristic parameters, freezing point depression, volumetric heat capacities for thawed and frozen conditions, thermal conductivity for thawed and frozen conditions and the depth of the layer. The moisture content is constant in time for GIPL 2.1 used in this study. The unfrozen water content is calculated according to the following equation based on Lovell (1957): $\theta_l = \theta_{\mathrm{tot}} \cdot A \cdot (D - T)^B$ where θ_l [$\mathrm{m^3\,m^{-3}}$] is the volumetric unfrozen water content at temperature T [°C], θ_{tot} is the total volumetric water content of the soil, D is the freezing point of the material (available to allow adjustment of the freezing point to account for solutes in the domain), and A and B are parameters that vary based on the material in question. The unfrozen water content is truncated to the total water content if $\theta_l > \theta_{\mathrm{tot}}$. The distribution of thermal properties is based on the global soils map (Food and Agriculture Organization of the United Nations, 1978). The thermal properties and soil layering are based on experience with the GIPL model and measurements from numerous permafrost regions in the world. Vegetation, hydrology and organic material accumulation in the upper soil layers are the basis for the selection of the thermal properties, these variables are all reflected in the soils of a particular regions. We used therefore soil classifications to determine the distribution of thermal properties and layering of the grounds profile. For this run we use 10 different ground thermal classes illustrated in Fig. 1. Each class is based on a soil type described in Food and Agriculture Organization of the United Nations (1978). None of the classes include layers of soil with a freezing point depression, such as saline soils. For the general model run the variable $D = 0$ for all layers in all classes.

The second run for the Greenland domain shows the temperature distribution for a bedrock material. The material properties used for this run are kept constant for the entire domain so all variations shown are caused by spatial and temporal variations in the forcing temperature and snow depth. The thermal properties are the same for the entire depth of the profile and set to the values shown in Table 1 for the deepest layer of the first group, except for the moisture content, which is set to 0.1.

Snow is an important factor in permafrost temperature development (Lawrence and Slater, 2008; Goodrich, 1982). For the spatially distributed simulations we treated snow the same for sediment and bedrock areas. The data were taken from HIRHAM snow water equivalent projections. Snow depth was calculated from snow water equivalent using a constant snow density of $0.15\,\mathrm{gr\,cm^{-3}}$ in order the generate snow depth data that are comparable with the measured data from Ilulissat (Olesen, 2003), see Fig. 2. Snow thermal properties where calculated seperately. The discrepancies are due to the fact that snowfall is a model-generated quantity, so that storm patterns and intensities differ from real world data. Snow has a longer term effect on the ice content in the lower part of the active layer. Low snow years may result in increase in the ice content within the lower portion of the active layer (Daanen et al., 2008) and high snow years in discontinuous permafrost can prevent the freeze-up of the active layer and establish a talik, or a thawed layer in the ground (Yoshikawa and Hinzman, 2003). Bedrock outcrops are likely to experience less snow than the poorly drained low lying pockets of sediment, because the exposed rock outcrop areas are generally windblown. The scale of the regional climate model HIRHAM 4.0, used for this study, does not resolve this sub-grid scale variation between exposed rock and sheltered pockets. Only a blowing snow model would be able to simulate these differences. Blowing snow is currently not a part of the snow routine in the latest version of the regional climate model HIRHAM

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5.0, but new development of the surface regime includes an ice sheet model and a blowing snow model based on the Snowpack Model (Liston and Elder, 2006). In our simulation we did not take the potential snow depth difference between bedrock and sediment pockets into account, because we do not have any data to support dividing snow accumulation between these distinct areas of interest.

2.1 Results

The Greenland simulation results presented are a 10 yr average temperature for current conditions and conditions 60 yr from now for 2 m depth. These data show an average increase of 1.28 °C in air temperature for the entire ice free portion of Greenland. Most of this warming is concentrated in the northern regions, with much less warming along the coast in the southwest where most communities are located. The simulation result using bedrock substrate shows that the 10 yr mean temperature at 2 m below the surface will increase by 1.56 °C and the simulation result using sediment will increase by 1.99 °C. The spatial trend is similar to the air temperature with most warming occurring in the north. Bedrock thaw depths will increase by 1.4 m on average for Greenland. The active layer in sediment will increase by 0.44 m between current and future conditions, the active layer depth varies strongly from north to south with the greatest increases in active layer occurring in the south.

Figure 3a shows the temperature distribution in bedrock material over Greenland at a 25 km resolution. The first image is the ten year average ground temperature from 1955 till 1965 for a depth of 2 m and the second images is the same parameter for the recent soil climatic conditions (1995–2005) at the same depth and the last image is a projection into the future soil climate for the simulation period from 2065 till 2075. Close inspection of the images shows a small amount of warming over most of the simulated area. In bedrock the temperature fluctuation between summer and winter are larger than in the sediment due to strongly reduced amount of ice or liquid water that buffers the temperature fluctuation (Romanovsky et al., 2010). Figure 3b shows the active layer depth for the beginning (left), middle and the end (right) of the simulation period.

The active layer depth reflects the same limited buffer capabilities with deep summer effective active layer depth in the bedrock of more than 3 m.

For undisturbed sediment we found cooler average temperatures due to the thermal offset in the upper soil layers. In addition there is a larger quantity of liquid water present and a larger amount of ice in the winter compared with the bedrock simulations. The 2 m temperature and active layer results for the sediment simulations are given in Fig. 4a. Figure 4b for the active layer depth. The results show a warming trend over our simulation period and a deepening of the active layer. Most of the warning occurred in winter which leads to warmer permafrost, but not directly to a deeper active layer depth in the northern portion of Greenland. However in the south summer temperatures increase also and there active layer depths are clearly affected. It is also clear from the simulations that permafrost in some southern most sediment regions will completely disappear. The boundary for sporadic permafrost is expected to migrate north by as much as 50 km.

2.2 Risk assessment methodology

A new simple risk assessment scheme is presently being developed at the Arctic Technology Centre at DTU-BYG in cooperation with the Permafrost Laboratory at GI, UAF. The methodology aims at determining the risk of permafrost degradation resulting in severe settlements. The model can be applied on a regional scale to produce forecasts of likely scenarios, or in a site specific context as a decision and planning tool for town planners and engineers in the local municipal governments and consulting businesses in the Greenlandic towns. In the present study we focus on the regional approach in order to produce a risk assessment indicating the likely changes for the 21st century over the entire Greenland domain.

Risk is classified in the four categories Low, Limited, Medium and High risk based on environmental variables and a thermal criterion. The three main variables are sediment or rock type, presence of ice/water, and the ground thermal conditions. The state of these variables are either determined from field investigations or estimated based on

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background information such as geological maps and modeling efforts. For the thermal criterion, we have chosen to define what we call the Permafrost Thaw Potential (PTP).

2.2.1 Permafrost Thaw Potential

The present permafrost is at risk for both future climatically induced warming and surface condition changes due to infrastructure development and constructions. The two effects act in a complementary additive fashion. The projected climate induced changes result in increased active layer thicknesses and have been elaborated in the previous sections of this paper (see Figs. 3b and 4b).

The risk arising from infrastructure development on permafrost is also a deepening of the active layer resulting from removal of the insulating organic layer and replacement with asphalt concrete which changes the surface energy balance and the thermal properties of subsurface material. Heat-carrying or producing structures such as housing, pipelines and sewers, produce additional heat conduction into the ground and may induce further thawing.

The regional risk should therefore be evaluated based on simulations of permafrost conditions in the original sedimentary setting and compared to thermal conditions under the forecasted future conditions. We define here the Permafrost Thaw Potential (PTP) as the potential active layer increase by subtracting the current active layer thickness from the expected active layer thickness under the future climatic and surface conditions.

In this study we suggest using the modeled bedrock situation as a proxy for disturbance due to infrastructure development in terms of removal of organic layer and change of surface energy balance. The current and future active layer depths for bedrock are given in Figs. 4b.

In this way the PTP becomes an indication of permafrost "health" for the next 60 yr taking into account possible future construction effects.

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2.2.2 Work flow

Figure 5 illustrates a flow diagram with environmental variables resulting in different risk classifications, and typical foundation solutions recommended for each class. Variable where chosen based on foundation support capabilities. Bedrock is the best supporting medium, then gravel then frozen soil and lastly thawed fine grained soil.

The general work flow in applying the risk assessment would be to:

1. evaluate surface properties: Bedrock, soil/vegetation, water content,
2. establish an engineering geological model of the area,
3. produce projection of future ground temperature regime and calculate PTP,
4. risk evaluation according to flow chart,

2.3 Risk Assessment for the Greenland domain

Figure 6 shows the PTP evaluation for the entire Greenland domain. Most of the terrestrial portion of Greenland is at risk of permafrost degradation. The high risk is mainly present in the southern permafrost region and the low risk in the far North. Thule Air force base is located in a transitional area from low risk to high risk. This is also supported by settlement of large structures on the Air force base. Modern buildings with sophisticated cooling mechanism are stable whereas older buildings without these systems settle (Birkholm et al., 2007).

To quantify the risk using the PTP we classified it to a high and low intervals with a limiting PTP value of 2.5 m, which makes most of the inhabited land vulnerable to permafrost degradation with the boundary in the vicinity of the Thule air force base. The modeled PTP classification can be combined with the lithological information from the permafrost model as well as estimations of ice contents to form the decisional basis of applying the risk zonation strategy.

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2.4 Model validation and implications on a community scale

In order to validate the results of our model and classification scheme, we estimated the predicted effects of permafrost degradation at the grid cells representing two major towns of Sisimiut and Ilulissat. The towns are both located in the permafrost affected region of West Greenland. We compare here the model results with observed data from the two localities.

2.4.1 General geological background

In most of the inhabited parts of West Greenland, bedrock is generally observed in outcrop or very near to the ground surface. Sediments are mainly found in local bedrock depressions.

All of Greenland was ice covered during the last glaciation (Weichsel-Wisconsin), and the ice retreated from the west coast around 10 000 yr ago (Roberts et al., 2009; Bennike and Björck, 2002). At that time, the local sea level is expected to have been 70 to 150 m above the present level (Rasch, 2000), and a series of marine silt and clay rich sediments were deposited on the sea bottom. Interaction between eustatic changes and isostatic uplift raised the area above sea level between 6000 and 8000 yr ago, exposing these sediments to freshwater percolation and depletion of salts. We speculate that the desalination process stopped some time after the end of the Holocene Climatic Optimum around 5000 BP, due to the formation of the near-surface ice-rich permafrost which hindered further percolation.

2.4.2 Results and implications at Sisimiut

Sisimiut is situated on the west coast of Greenland at approximately 66.2° N and 53.7° W (see Fig. 6). According to the permafrost distribution map of Christiansen and Humlum (2000), Sisimiut is located in the discontinuous permafrost zone.

In the 1960s and 1970s, the Geological Survey of Greenland operated a ground temperature measurement station in Sisimiut (Olesen, 2003), with temperature sensors down to a depth of 9 m. The availability of this data and a few years of modern data allows us to investigate the model performance over more than a decade. Figure 7 shows a plot of the modeled ground temperature data as well as the observed data. The results show that the surface conditions (0.25 m depth) are fairly well simulated, with similar amplitudes but slightly warmer temperatures in the model. The deeper permafrost temperatures are underestimated by the model, likely a result of vegetation disturbance in the area where the observed data were collected. Overall the model shows that permafrost temperatures are warming over the next decades.

With Sisimiut situated in the discontinuous permafrost zone, ground temperature conditions are expected to vary widely on a local scale depending on surface conditions, lithology, water content, slope aspect etc. While the location chosen for the ground temperature observations by Olesen in 1967 can be only barely categorized as permafrost (at that time), other locations in town are known to have ice rich permafrost (Ingeman-Nielsen, 2005; Ingeman-Nielsen et al., 2007). Obviously this local scale variation cannot be described using a regional model with a grid size of 25 km. With this in mind, the agreement between observed and modeled ground temperature data seems reasonable. The soil at the measurement site in Sisimiut is coarser grained and better drained than it is assumed in the model. This results in lower water/ice contents compared to parameters used in the model and in less organic matter buildup, shading and evapotranspiration during the summer. These differences lead to higher subsurface temperatures at the observational site compared to the model simulation.

As the model forecasts a warming trend in the ground temperatures over the course of the century, and present modeled permafrost temperatures are as high as $-1\,^{\circ}$C, it is clear that soon permafrost will be actively degrading in the Sisimiut area.

We have calculated the PTP for the Sisimiut region to be 4.5 m, which indicates a high risk of thaw induced settlements in connection with the fine grained marine deposits that are widely occurring in the area. Based on the modeled PTP, all permafrost areas with basin deposits of marine silty clay are classified as high risk zones.

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2.4.3 Results and implications at Ilulissat

Ilulissat is situated in the inner part of the Disko Bay at approximately 69.2° N and 51.1° W (see Fig. 6). The locality is a well documented example of saline permafrost (Ingeman-Nielsen et al., 2008; Foged and Madsen, 1980) under discontinuous permafrost condition as shown in the Permafrost distribution map for Greenland of Christiansen and Humlum (2000). Sediment distribution for the township is illustrated in Fig. 8. These sediment regions are tightly woven throughout vital areas in Ilulissat. The pressure to expand infrastructure and housing drive the push toward development of this land.

Detailed geotechnical investigations in this area (Foged, 1979) have shown that the fine grained marine deposits are not completely leached. Comparisons of pore water chemistry show that the extent of desalination seems to be related to elevation. Areas at higher elevations show deeper extent of desalination due to longer exposure before permafrost aggradation starts. The lower lying areas are only desalinated in the upper 3–6 m with chloride concentrations nearing those of seawater in the deeper parts of the profiles 4 m till bedrock.

The ice content of the sediments in the Ilulissat area depends on both salinity and the availability of water at the time of permafrost formation, and spans a wide range from almost no excess ice to segments with gravimetric water contents of several hundred percent due to the presence of ice lenses (Ingeman-Nielsen et al., 2008).

In addition to the previously described regional model run, we have also modeled a completely unleached saline situation for Ilulissat, using a freezing point depression of 2 °C for all layers in the model ($D = -2$ °C).

Figure 9 illustrates the observed and simulated ground temperature evolution for sedimentary deposits in the Ilulissat area for completely leached as well as saline conditions at the depths of 2.5 and 15 m. The model results show that the presence of residual salinity in the sediment causes a significant attenuation of the amplitudes of the annual temperature oscillations, due to the additional energy consumed/produced

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during phase changes in the deeper active layer. The results indicate an increase of a little more than 1 °C in mean annual ground temperature by 2080 as compared to 2009.

The Geological Survey of Greenland also operated a ground temperature measurement station in Ilulissat (Olesen et al., 2003) in the 1960s and 1970s. The Ilulissat ground temperature station was equipped with temperature sensors down to a depth of 15 m. New data more recently collected of the upper 4 m of permafrost close to the airport in Ilulissat is also presented. The observed data has been added to the Fig. 9 for comparison.

The simulation results from 2.5 m depth and unleached conditions fit well with the observed data, although winter temperatures are generally colder in the model prediction.

Similarly to the Sisimiut simulations, the deeper permafrost temperatures of the Ilulissat simulations are too cold compared with the observed data. The observation point chosen by Olesen was located in a fairly small sediment-filled bedrock depression and it is possible that the measured bedrock temperatures are affected by heating from outcropping bedrock in near proximity of the measurement site, causing the difference between observed and modeled temperatures.

Overall the temperatures are rising over the simulation period and active degradation of permafrost in this area is expected.

The agreement between observed and modeled ground temperatures is very good, with average temperature difference within 1 °C. Especially noticeable that the amount of snow (Fig. 2), which is an important variable for the ground temperature, was exclusively simulated by HIRHAM.

The calculated PTP for the Ilulissat region is 3.7 for the leached condition and indicates a high risk of thaw induced settlements in connection with fine grained marine deposits that are widely occurring in the area. Based on the modeled PTP, all permafrost areas with basin deposits of marine silty clay are classified as high risk zones.

2.5 Discussion

The data provided in Figs. 3a and 4a are ten year average ground temperatures to minimize weather effects on permafrost temperatures. The data shows a modest amount of change over the simulation period from 1950 till 2075. Even the higher spatial resolution (25 km) of the HIRHAM regional climate model simulation of air temperatures and snow depth is relatively coarse when comparing it with the heterogeneity of the landscape (Stendel et al., 2008b). The north-south gradient of the climate matches the observed permafrost temperatures reasonably well (Christiansen and Humlum, 2000). Improvement in resolution is needed to simulate the smaller scale dynamics from the coast inland, considering the numerous fjords along the coast. Temperatures in the northern part of Greenland seem to be most affected by the warming climate. The active layer thickness is sensitive to the warming trend.

One of the drawbacks of present state-of-the-art regional scale permafrost models is their lack of ability to handle segregated ice in the sediments. The model applied here can handle high volumetric water contents, but as the model is not coupled to a groundwater flow and drainage model, such high water contents would be static in location and thus cause unrealistic distribution of water in the active layer upon permafrost thaw. The model has therefore been implemented using water contents on the order of natural porosity of the sediments, causing probably an underestimation of ice content in the upper part of the permafrost.

Climate warming in the Sisimiut and Ilulissat region causes the active layer thickness to increase in bedrock from less than 3 m to greater than 3 m. For sediment areas, which are important for new development of infrastructure, the active layer deepens from approximately 1 m now to 2 m in 2075, assuming the constant ice content with depth. This sediment warming is based on the one-dimensional simulations and does not include the potential thermal effect of bedrock surrounding these sediment pockets, which can dramatically warm the permafrost inside the sediment pockets. The large amount of ground ice observed in these sediments could result in soil surface

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settlement of up to 1 m. The PTP shows a high risk for both Sisimiut and Ilulissat regions.

The risk of permafrost degradation for engineering structures is strictly related to the presence of sediment around the community of interest. The current conditions in sediments around larger communities like Sisimiut and Ilulissat would not support construction of larger buildings. The soil temperatures are near the thawing point of the saline permafrost during the summer months. As indicated by the PTP the additional stress of climate warming and soil surface disturbance makes the situation more unsuitable.

Due to its present resolution (25 k), the applied PTP approach can technically not be used as design criteria for individual projects. However, the high-resolution PTP mapping may be used during site specific permafrost analysis to determine the particular permafrost degradation risk for that site. This site specific permafrost degradation risk designation will assist with design and expense evaluation due to mediation techniques against aversive affects of construction on permafrost. In the cases of Sisimiut and Ilulissat we classify the PTP as a high risk because most of the ice rich permafrost is warm and at risk of degrading. This means that the cheapest solution to protect infrastructure and buildings is to remove perennially frozen soils and substitute them with non-frost-susceptible materials or to use point-bearing piles resting on bedrock.

3 Conclusions

3.1 Modeling results

Permafrost temperatures were simulated for Greenland and it was found that most areas are warming as the climate warms over the period from 1950 till 2075, although the changes are relatively small. Permafrost temperatures in the northern portion of the country are strongly affected by warming winter temperatures whereas the temperatures in the south are buffered by melting ground ice and deepening of the active layer. The active layer thickness is increasing with time for bedrock and sedimentary substrates indicating summer warming.

We quantified the risk of climate warming and surface alteration on permafrost degradation using the PTP. Most of the terrestrial regions in Greenland south of 76 degrees are at high risk of permafrost degradation, which means that any type of construction on ice rich sediments is not advised.

3.2 Geotechnical recommendations

Infrastructure and buildings that are currently not resting on bedrock will become exposed to uneven settling of sediments and potential degradation. We expect construction and maintenance costs of buildings and infrastructure in Greenland to increase dramatically if current practices are not adapted to the warming conditions. We have suggested a simple risk assessment methodology developed specifically for Greenlandic conditions that could help local municipal governments and contractors to assess the local risk of permafrost degradation, and help in determining the proper site investigation strategies and foundation practices for individual construction projects.

The Simiut and Ilulissat areas are both in risk of severe permafrost degradation due to the presence of permafrost with temperatures close to the freezing point of the ground materials. For the town of Ilulissat in particular, the combination of saline permafrost with a high ice content and a high Permafrost Thaw Potential results in a high risk scenario where construction on fine-grained sedimentary deposits with permafrost should be avoided whenever possible, either by excavation of the sediments or by construction of point bearing piles extended to bedrock surface.

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With the discovery of America (Columbus, 1492) a new continent was opened up. However its full exploitation by Europeans and their offspring was not fully complete until many centuries later, as reported by James et al. (1776).

During this interval, known as the Winning of the West (Smith and Weston, 1954), a major role in the development of the continent was played by the lowly revolver (e.g. Green et al., 1900). Recently, Phillips (1999) suggested that the magnetosphere could have played an even more significant role. In order to pursue this conjecture, the authors of this work have carried out a historical survey and have found startlingly little evidence for such a claim.

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Table 1. Parameters in the sediments classification. For the bedrock simulation, all models are assigned the parameters of the deepest layer of Group 1 (highlighted in the table) except for the volumetric water content which is set to 0.1.

Vol. Wat. [%]	Un. Wat. par. *A* [–]	Un. Wat. par. *B* [–]	Un. Wat. par. *D* [°C]	H. Cap. Thawed [$J\,m^{-3}\,K$]	H. Cap. Frozen [$J\,m^{-3}\,K$]	Th. Con. Thawed [$W\,m^{-1}\,K$]	Th. Con. Frozen [$W\,m^{-1}\,K$]	Depth [m]
Group 1								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.4	0.75	0.15
0.65	0.02	−0.38	0	2 600 000	2 400 000	0.5	1.6	0.3
0.65	0.035	−0.35	0	2 700 000	2 200 000	0.5	1.6	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.4	0.05	−0.35	0	2 900 000	2 000 000	1.2	3	10
0.4	0.05	−0.35	0	2 900 000	2 000 000	0.9	2.2	20
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 2								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.6	0.75	0.05
0.65	0.035	−0.35	0	2 700 000	2 200 000	0.8	1.6	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 3								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.5	0.6	0.1
0.65	0.035	−0.35	0	2 700 000	2 200 000	0.8	1.6	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	5
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 4								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.4	0.6	0.2
0.65	0.035	−0.35	0	2 700 000	2 200 000	0.7	1.6	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	1.1	2.2	3
0.4	0.05	−0.35	0	3 000 000	1 700 000	1.2	3	10
0.4	0.05	−0.35	0	3 000 000	1 700 000	0.9	2.2	20
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000

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Table 1. Continued.

Vol. Wat. [%]	Un. Wat. par. *A* [–]	Un. Wat. par. *B* [–]	Un. Wat. par. *D* [°C]	H. Cap. Thawed [$J\,m^{-3}\,K$]	H. Cap. Frozen [$J\,m^{-3}\,K$]	Th. Con. Thawed [$W\,m^{-1}\,K$]	Th. Con. Frozen [$W\,m^{-1}\,K$]	Depth [m]
Group 5								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.6	0.8	0.15
0.65	0.035	−0.38	0	2 700 000	2 200 000	1	2	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	1.1	2.2	3
0.4	0.05	−0.35	0	3 000 000	1 700 000	1.2	3	10
0.4	0.05	−0.35	0	3 000 000	1 700 000	0.9	2.2	20
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 6								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.7	0.9	0.1
0.65	0.035	−0.38	0	2 700 000	2 200 000	1	2	1.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	1.1	2.2	5
0.4	0.05	−0.35	0	3 000 000	1 700 000	0.9	2.2	10
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 7								
0.25	0.002	−0.1	0	1 700 000	1 600 000	0.4	0.75	0.3
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.4	0.05	−0.35	0	3 000 000	1 700 000	1.2	3	10
0.4	0.05	−0.35	0	2 900 000	2 000 000	0.9	2.2	20
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000

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Table 1. Continued.

Vol. Wat. [%]	Un. Wat. par. *A* [–]	Un. Wat. par. *B* [–]	Un. Wat. par. *D* [°C]	H. Cap. Thawed [J m^{-3} K]	H. Cap. Frozen [J m^{-3} K]	Th. Con. Thawed [W m^{-1} K]	Th. Con. Frozen [W m^{-1} K]	Depth [m]
Group 8								
0.3	0.002	−0.1	0	1 700 000	1 600 000	0.4	0.75	0.5
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.4	0.05	−0.35	0	2 900 000	2 000 000	1.2	3	10
0.4	0.05	−0.35	0	2 900 000	2 000 000	0.9	2.2	20
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 9								
0.3	0.002	−0.1	0	1 700 000	1 600 000	0.6	0.9	0.5
0.45	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.4	0.05	−0.35	0	3 000 000	1 700 000	1.2	3	10
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000
Group 10								
0.4	0.002	−0.1	0	1 700 000	1 600 000	0.6	0.9	0.5
0.55	0.06	−0.35	0	2 900 000	2 000 000	0.9	2.2	3
0.4	0.05	−0.35	0	3 000 000	1 700 000	1.2	3	10
0.2	0.01	−0.17	0	2 800 000	2 000 000	2.8	3.5	1000

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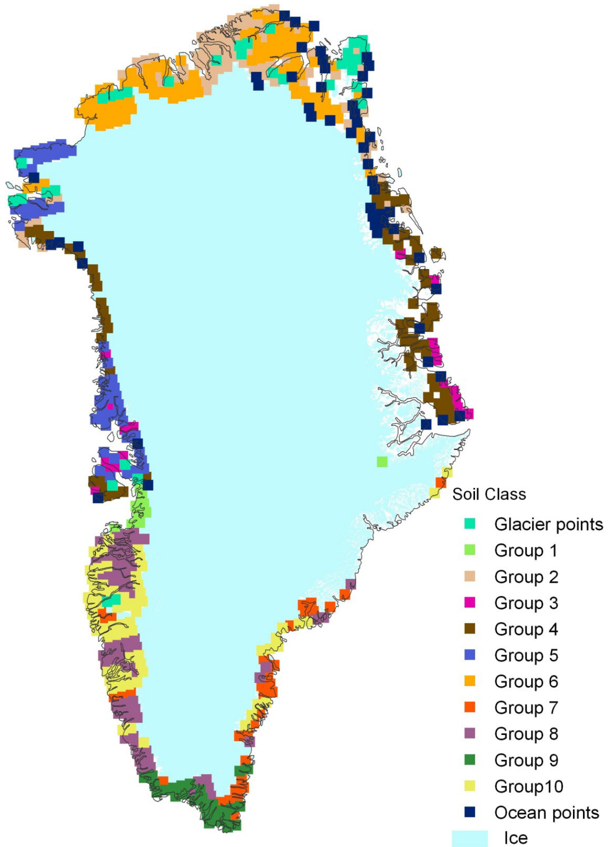

Fig. 1. Soil classification zones.

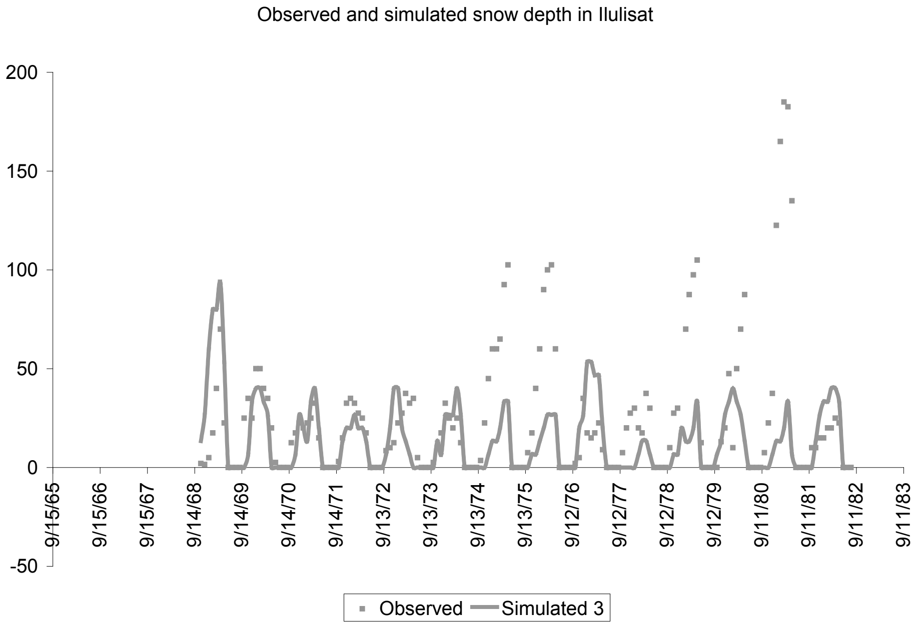

Fig. 2. Observed and simulated snow depth for the Ilulissat region.

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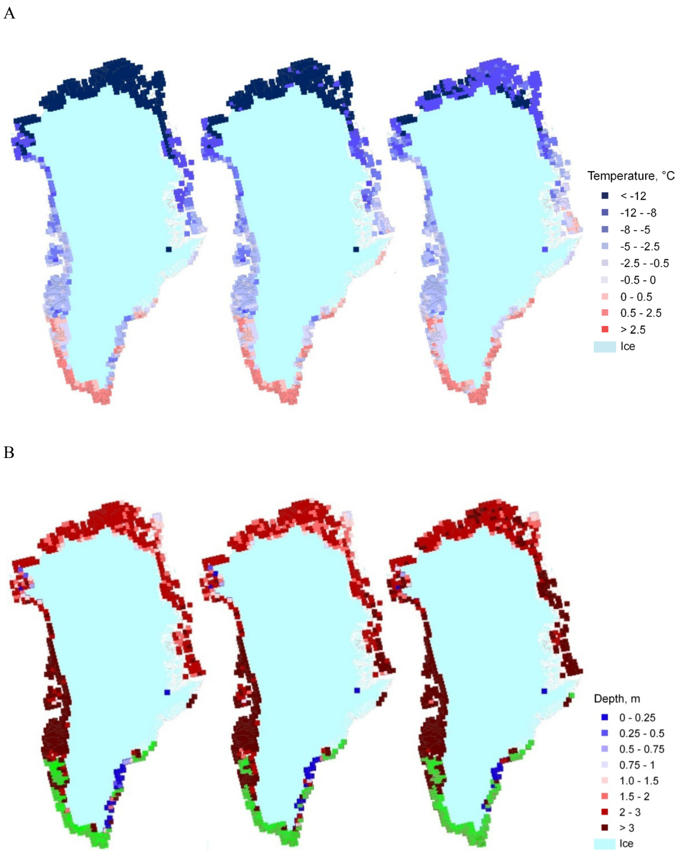

Fig. 3. **(A)** Bedrock temperature distribution at 2 m depth for an average over the periods 1955–1965, 1995–2005, and 2065–2075. **(B)** Active layer depth distribution in bedrock for an average over the periods 1955–1965, 1995–2005, and 2065–2075. The green color represents a permafrost free zone.

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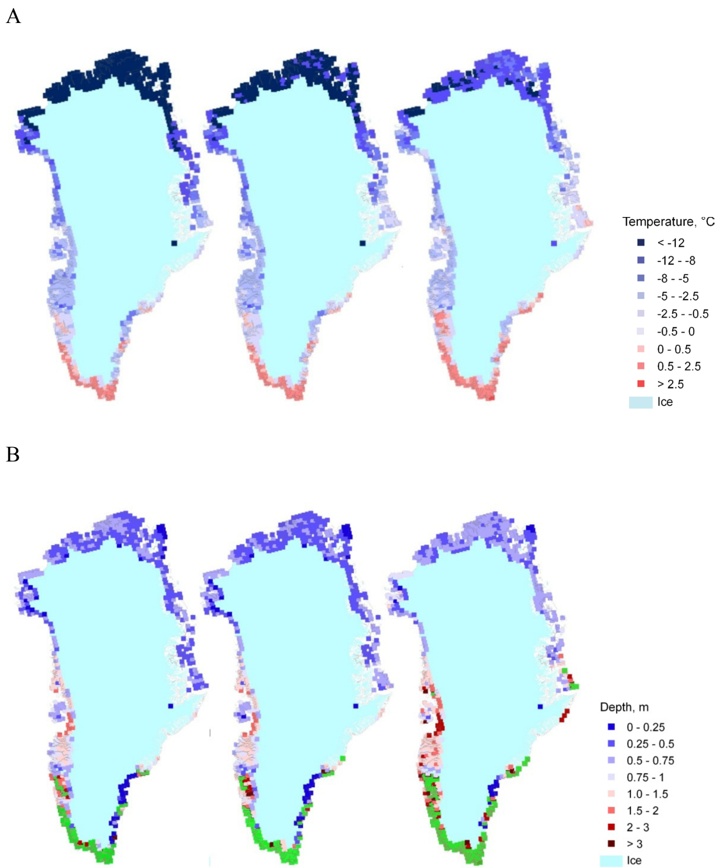

Fig. 4. **(A)** Annual average ground temperature distribution at 2 m depth in sediment with organic layer averaged over the periods 1955–1965, 1995–2005, and 2065–2075. **(B)** Active layer depth distributions for areas with sediments and organic matter averaged over the periods 1955–1965, 1995–2005, and 2065–2075. The green color represents a permafrost free zone.

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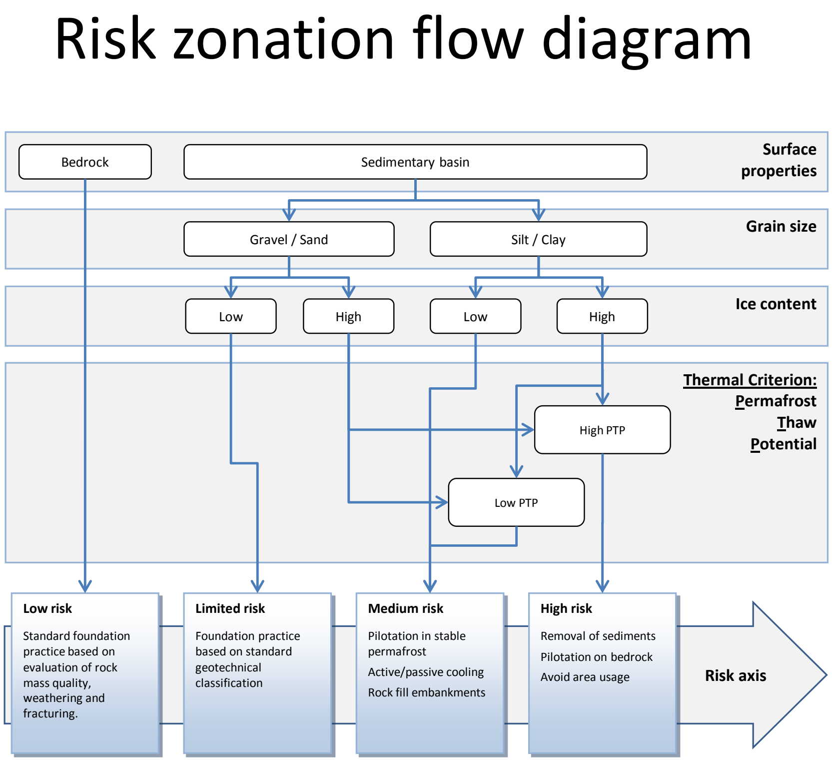

Fig. 5. Risk evaluation decision flow diagram for permafrost affected areas.

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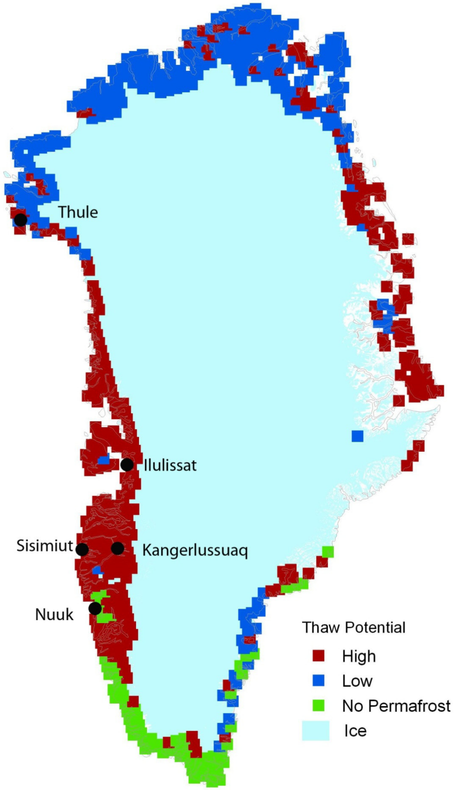

Fig. 6. Permafrost Thaw Potential for Greenland. High thaw potential coresponds with a greater than 2.5 m potential active layer depth increase. The potential active layer depth increase was calculated by subtracting current sediment active layer depths from future bedrock active layer depths.

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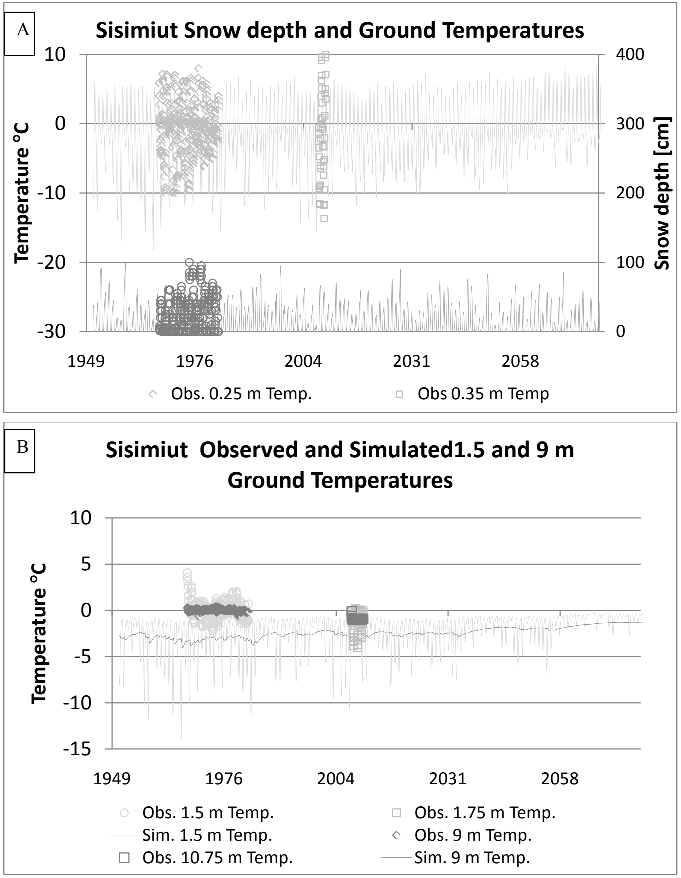

Fig. 7. Observed and simulated snow depth and ground temperature at 0.25 m **(A)** and ground temperatures at 1.5 m and 9 m **(B)** near the Sisimiut area for the entire simulation period.

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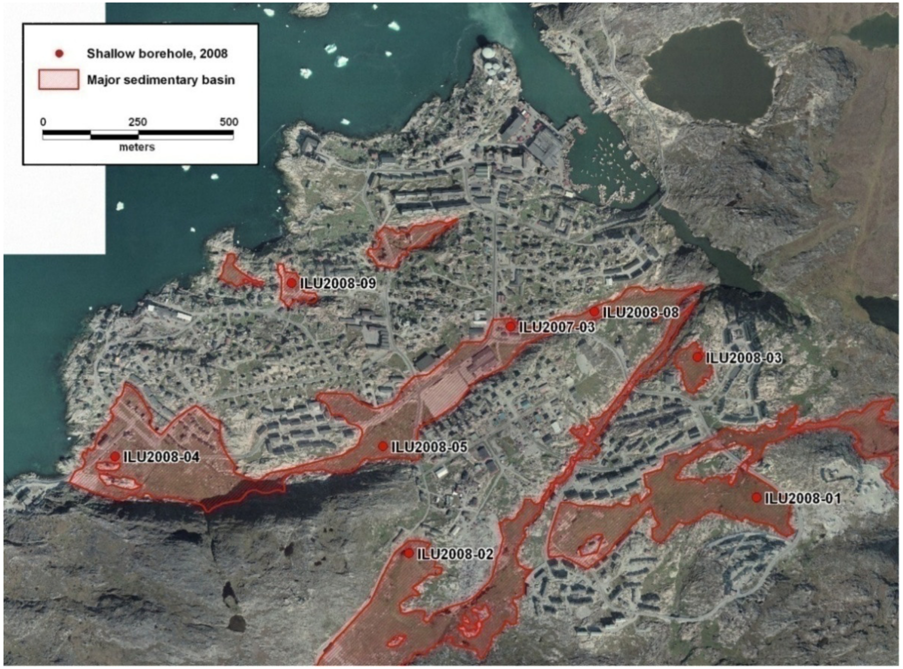

Fig. 8. Ortho photo showing Ilulissat town area. Shallow boreholes conducted in 2007 and 2008 are indicated, and major sedimentary basins outlined. These are all considered High Risk areas, due to the special combination of fine grained sediments, residual pore water salinity and in many cases high ice content.

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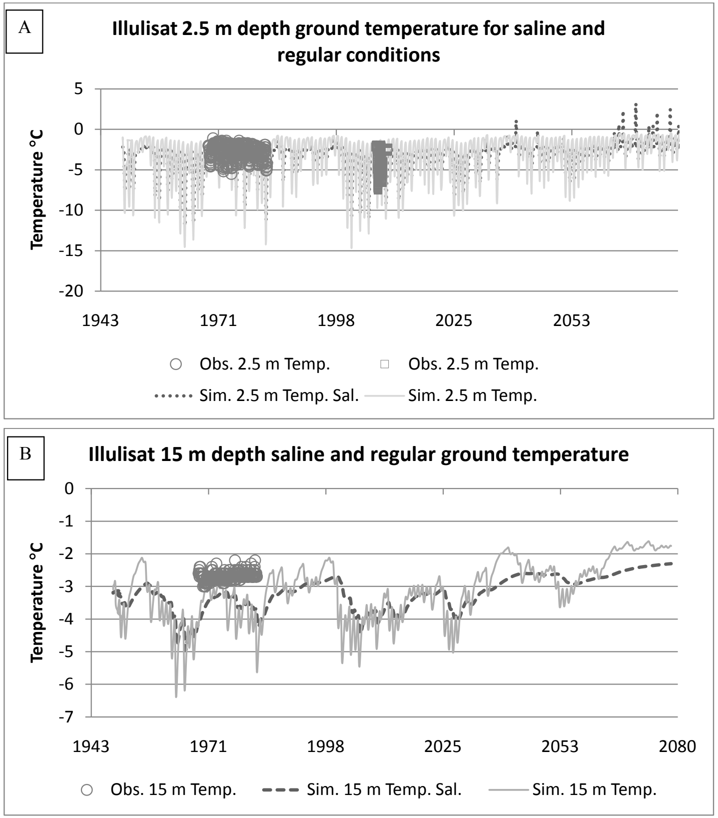

Fig. 9. Temperature time series for an area near Ilulissat for 2.5 m depth **(A)** and 15 m depth **(B)**, comparing saline and regular temperature simulation in a sediment pocket.