Temperatures in Coastal Permafrost in the Svea Area, Svalbard

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Abstract

Temperature data from three boreholes located on an ice-cored moraine near sea level are analyzed. One of these boreholes was drilled 6 m from the shore and shows significantly higher temperatures than the holes about 150 m from the shore. Using meteorological data and measurements of water temperatures, we model the permafrost distribution into the fjord as well as the influence of the sea on permafrost temperatures near the shore. The model results suggest that permafrost, as defined solely on temperature, is present beneath Van Mijenfjorden.

Keywords: borehole temperatures; coastal; geothermal modeling; permafrost; subsea permafrost; Svalbard.

Introduction

Permafrost on Svalbard is classified as continuous. It is more than 500 m thick in the highlands and less than 100 m near the coasts (Humlum et al. 2003). While considerable knowledge of permafrost conditions in the mountains exists from the extensive coal mining, little has been published on the permafrost in the shore areas of Svalbard. Exceptions are Gregersen & Eidsmoen (1988) that compares deep borehole temperatures at the shore with inland boreholes in Longyearbyen and Svea, and Harada & Yoshikawa (1996) that uses DC resistivity soundings to estimate the permafrost thickness of marine terraces at the shore of Adventfjorden near Longyearbyen.

The aim of this paper is to describe the permafrost conditions in the ice-cored moraine, Crednermorenen,a peninsula in Van Mijenfjorden in central Spitsbergen (Fig. 1). Since April 2005 temperatures have been logged every two hrs in three boreholes on the moraine each with 16 thermistors down to eight m. One of the boreholes is located only six m from the shoreline. Permafrost conditions in the shore area are important since the permafrost here is "warm" and thin. When constructing in such areas, particular attention must therefore be given to the permafrost conditions. In most other parts of Svalbard, permafrost is thicker, colder and more stable.

Due to the few previous studies of near-shore permafrost on Svalbard, an attempt was made to model both the effect of the sea on the onshore permafrost as well as the possibility of subsea permafrost. We use a transient 2D finite element geothermal model (TEMP/W from Geoslope International, Calgary, Canada; Krahn 2004) that is forced with meteorological data and measured water temperatures as boundary conditions.

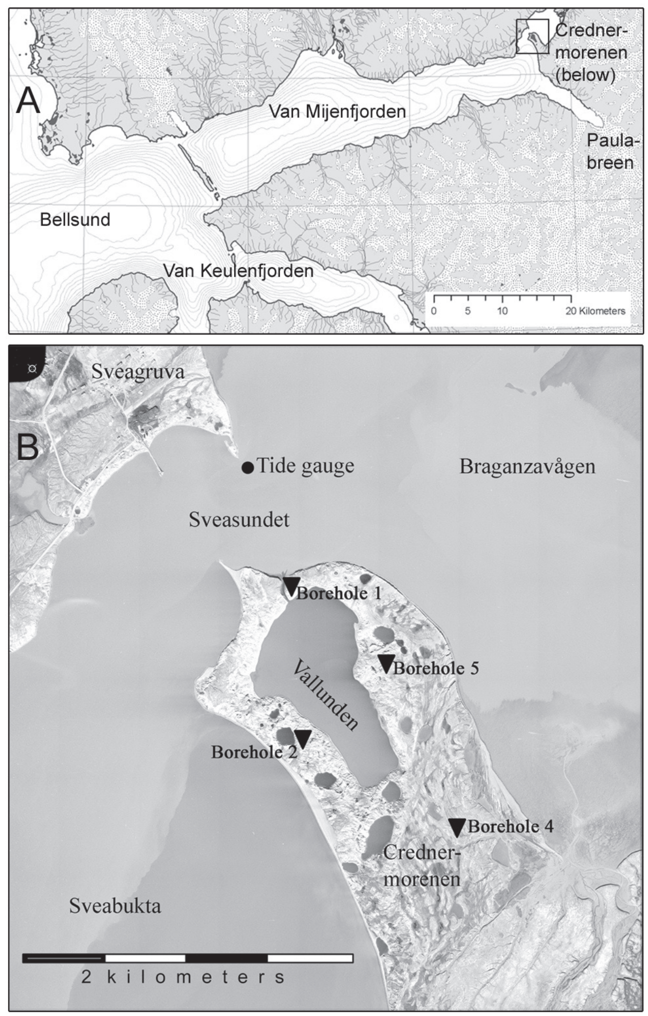

Figure 1. Field site. A) Van Mijenfjorden with Crednermorenen (in upper right corner). Map from: http://www.iopan.gda.pl. B) Crednermorenen with the location of the boreholes and the tide gauge. Air photo: Norsk Polarinstitutt, 1977.

Field Site

Crednermorenen is a lateral moraine deposited by a surge of the tidewater glacier Paulabreen (Fig. 1) around 1300 A.D. (Hald et al. 2001). The moraine forms a peninsula (1x3 km),

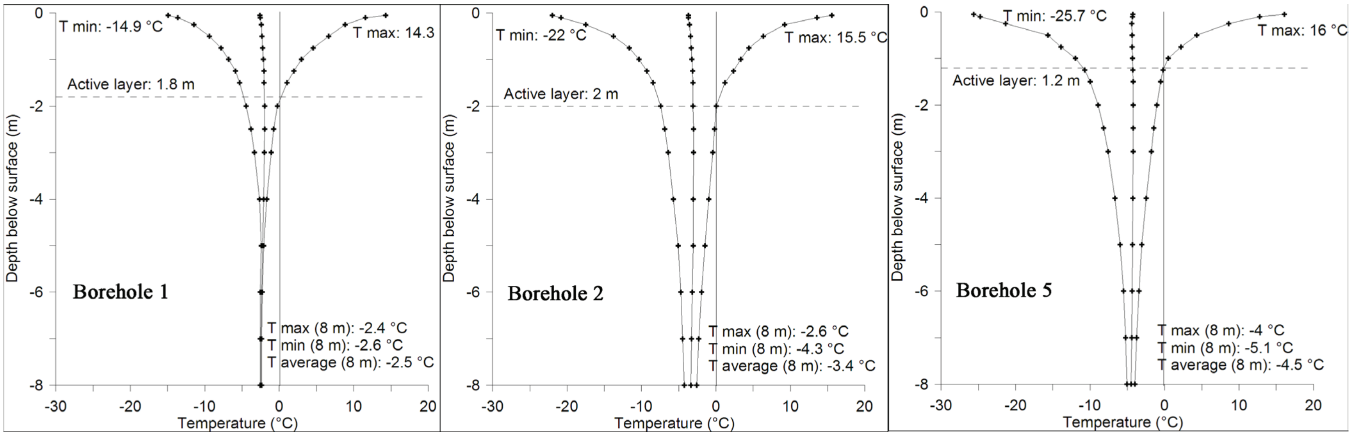

Figure 2. Maximum, minimum, and average temperatures in all depths from 10 September 2006 to 9 September 2007 for Boreholes 1, 2, and 5.

Table 1. Average annual temperature at the ground surface, at the top of the permafrost (TTOP).

	(Air)	Hole 1	Hole2	Hole 5
T surface (°C)	-4.6	-2.6	-3.7	-4.2
TTOP (°C)		-2.0	-3.1	-4.3

partly ice-cored and partly consisting of proglacially pushed marine clays (Kristensen et al., in press). It is surrounded by water on three sides and in its northern part lies a 1 km long lagoon, —Vallunden—that, is connected to the sea by a 15m-wide channel near Borehole 1. The water in Vallunden is salty as the tide flows in and out through the channel.

The oceanography in Van Mijenfjorden is strongly affected by an island at the fjord mouth, Akseløya (Fig. 1A), which nearly blocks the water exchange between the fjord and the warmer Atlantic water outside (Nilsen 2002). The water column is thus dominated by cold local water. Shore-fast ice is usually present from December to June. Bottom water salinity is around 34‰ (Hald et al. 2001), and July temperatures of -1.53°C and and -1.27°C have been measured in two basins in Van Mijenfjorden at 112 m and 74 m depth (Gulliksen et al. 1985). The climate in Sveagruva is slightly colder and more humid than in Longyearbyen 45 km to the NNE, but the meteorological record is shorter and more irregular. Mean annual air temperature close to sea level was -5.4°C in the period 1997–2006, and precipitation in the period 1995–2002 was on average 244 mm/y (www.met.no).

Temperature Measurements in Boreholes

Four 10 m deep boreholes (Fig. 1B) were drilled on Crednermorenen in March 2005 using an air pressure driven drilling rig. Coring was not possible, but the pulverized blown up sediment was collected from three of the holes, described and analyzed for water content and salinity. Borehole 1 was located two m above sea level and six m from the channel that connects Vallunden with Sveasundet. Borehole 2 was drilled into the ice-cored part of the moraine 17 m a.s.l. and 150 m from Sveabukta. Borehole 5 was established on top of the moraine ridge 145 m from Vallunden and 20 m a.s.l. Hole four was located on the marine clay part of Crednermorenen, but was destroyed by a bear in October 2006, and therefore no data are presented from that hole. In each borehole an eight m thermistor string (EBA Engineering, Edmonton, Canada) with 16 thermistors at decreasing spacing towards the surface was inserted. The uppermost sensor in each hole was placed at roughly three cm depth, and was measuring the surface temperature in this paper. Temperatures have been logged every two hour using Lakewood dataloggers; the accuracy of the thermistors is around 0.1°C. The annual temperature envelopes recorded in the three boreholes are shown in Figure 2. The maximum surface temperature for holes one and five occurred on 16 July 2007, and for hole two on 18 June 2007. The maximum temperature was very similar for the three holes, probably indicating that the barren surface provided similar summer conditions. The minimum surface temperature for all three holes occurred on 23 January 2007, which was contemporary with the minimum air temperature (-32.9°C) being recorded. The minimum surface temperature was much lower in hole two and five than in hole one. The latter had usually a snow cover of around 20 cm whereas both holes two and five were usually snow-free in winter due to wind redistribution in these more exposed sites. In Borehole 1 the seasonal temperature fluctuation became insignificant (0.25°C) below six meters depth, whereas the difference between annual maximum and minimum temperature at eight m in Boreholes 2 and 5 were 1.7°C and 1.1°C respectively.

Table 1 shows that all ground surface temperatures in the investigated period were higher than the mean air temperature. Hole one was warmest, reflecting the thickest snow cover during winter. The snow insulated the surface against cold winter temperatures creating a positive surface offset as demonstrated by, for example, Smith & Riseborough (1996). Hole 5 had the smallest surface offset as this site is usually never snow covered.

Smith & Riseborough (1996) also demonstrated that, due to higher thermal conductivity in frozen ground than in unfrozen, temperatures will tend to decrease from the ground surface to the top of the permafrost table (TTOP). Table 1 shows

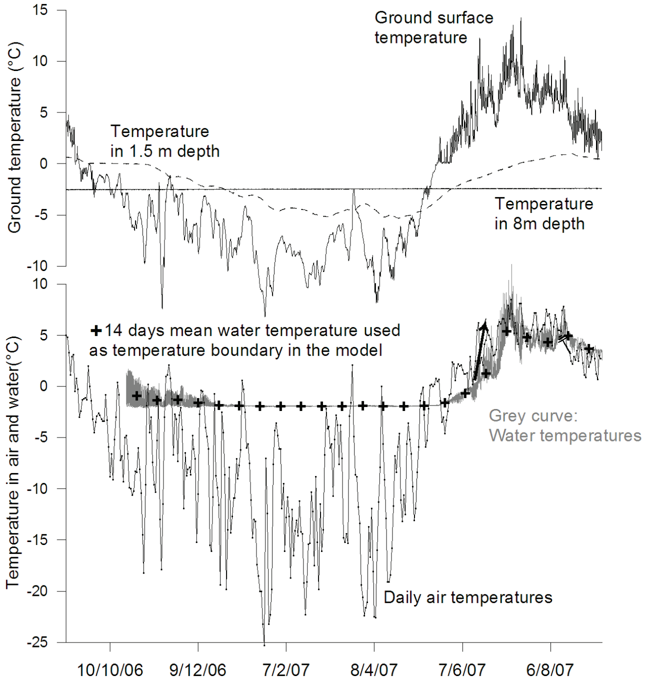

Figure 3. Upper part: Temperatures in Borehole 1 at the surface, in 1.5 m depth (dotted line) and in 8 m depth (no variation). Lower part: Air temperatures and water temperatures.

that in Boreholes 1 and 2 TTOP was higher than the surface temperature whereas in hole five it was practically the same. The active layer offset therefore seemed not to be important for the ground temperatures on the moraine, whereas snow depth in winter certainly was.

Tide and Water Temperature Measurements

Water temperatures in the narrow and shallow strait Sveasundet were measured and recorded every 20 min from 10 October 2006 to 9 September 2007 by a tidal gauge placed at two m water depth. The data can be seen in Figure 3 together with temperature measurements from Borehole 1 from three selected depths and air temperature measurements over the same time interval.

The freshwater from Kjellstrømsdalen passes the Sveasundet strait, and strong tidal currents flowing in and out of Braganzavågen ensure mixing of salt and fresh water here. For this reason the summer water temperatures were high compared to what has been measured in the deep basins in the fjord during summer. Winter temperatures however appeared to be constant around -1.93°C in most of the fjord.

The measured water temperatures can be divided in three distinct periods:

1) An autumn period when the temperature fluctuated in relation to the tide between -1.9 and +1.7°C lasting from 21 October to 26 December. Temperatures rose when the tide was moving through Sveasundet into the tidal flat Braganzavågen and fell when the tide flowed out again. This is consistent with observations that sea ice started forming in Braganzavågen before other places in the fjord. An example

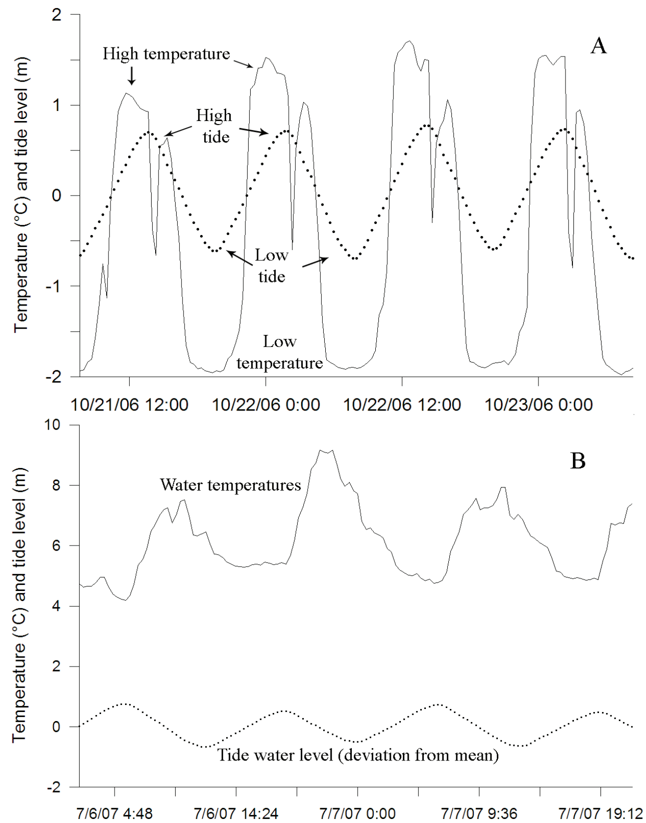

Figure 4. Examples of the relationship between water temperatures and the tide. A: Autumn conditions when the first sea ice forms, B: summer conditions.

of the coupling between tide and temperatures in the autumn can be seen in Figure 4A**.** November 28 was the last time the temperature rose above zero.

2) A winter period from 26 December to 22 May 2007. The temperature was nearly constant around -1.93, and no temperature fluctuations with tide were observed. The temperature corresponded to the freezing point of sea water and the fjord was covered by ice throughout this time. This winter period with constant water temperatures is easily identifiable in Figure 3.

3) A summer period from 22 May 2007 to the end of the measurements. Here the water temperatures increased and gradually approached the air temperature. The water temperature rose above zero for the first time on 13 June 2007. The temperature fluctuations were again controlled by tidal currents and were opposite in phase to those of the autumn. Now rising tide was associated with lower temperatures and falling tide with increasing temperatures (Fig. 4B). The reason is that water was now heated in the tidal flat Braganzavågen, where it was cooled during the autumn.

Modeling the Effect of the Sea on the Permafrost Temperatures

Studying the measured borehole temperatures, one can see that Borehole 1 deviated significantly from Boreholes

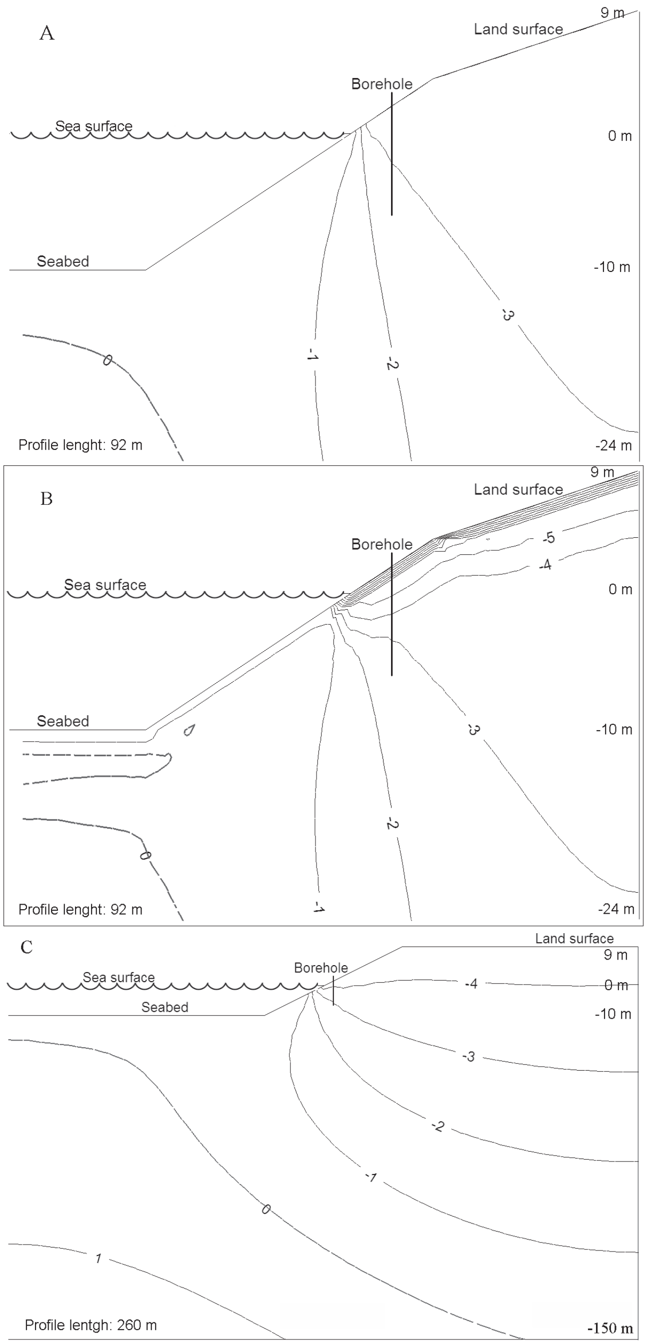

Figure 5. Three model output results. A: Steady state simulation of the ground temperatures in the immediate shore area. B: The same section but run in a transient mode forced with measured climatic data and sea water temperatures. Snapshot from 7 April 2007. C: Steady state simulation of a wider and deeper section with the boundary conditions the same as in A.

2 and 5 in respect both to the thermal regime and the depth of zero annual amplitude. While some of this deviation can be explained by a thicker snow cover during winter, most likely the proximity (6 m) to the sea affected the permafrost temperatures here. Located two m a.s.l. and being eight m deep, most of the borehole also lay below sea level. At eight m depth in Borehole 1, the temperature was -2.5°C. This indicates that permafrost probably extends into the seabed

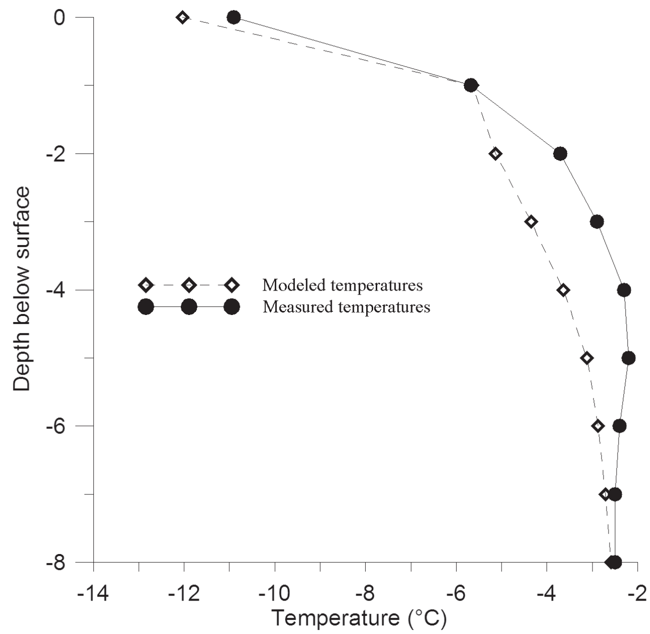

Figure 6. Comparison of the temperatures measured in Borehole 1 on 7 April 2007 and the modeled temperatures on the same day.

from the shore. An attempt was made to model both the effect of the sea on the onshore permafrost temperatures as well as the possibility of subsea permafrost existence. Gregersen & Eidsmoen (1988) previously tried to model the possible subsea permafrost in the area, but they had no information on the water temperatures in the fjord.

Model description and input

A 2D finite element program (TEMP/W) was used to model the permafrost thickness in Crednermorenen and the extent below the fjord bottom. The model is described in detail by Krahn (2004). Two temperature-dependent input functions (unfrozen water content and thermal conductivity) and overall water content are laboratory data from a nearby moraine, Damesmorenen, four km from hole 1, published by Gregersen et al. (1983). Volumetric heat capacity was set to 2000 and 3000 kJ/(m^3 x K) for frozen and unfrozen states respectively. Only one set of thermal properties was supplied to the model. It is obviously incorrect to assume homogeneous subsurface conditions, but we have no other thermal properties data available nor information on the subsea stratigraphy. A geothermal gradient of 35 mW/m^2 was set as a flux boundary condition at the bottom of the profiles. The vertical profile sides were set as zero flux boundaries.

To obtain a first estimate of the subsurface temperatures, the model was initially run in a steady state mode (Figs. 5A, 5C) using an estimated annual surface temperature and the average water temperatures as upper boundary conditions. A ground surface temperature of -4°C was used; this is slightly warmer than the mean annual air temperature due to the surface offset demonstrated in Table 1. A temperature of -0.1°C was used as the seabed boundary condition; this is the mean annual measured water temperature with interpolated temperatures for the missing 1.5 months of data.

The model was also run in a transient mode (snapshot in Fig. 5B) to compare the model results with the temperatures measured in Borehole 1. In the transient mode, eight simulations were run per day, and each node result was input to the next model run. Here the model was forced with meteorological data from 1 Jan 2006 to 10 September 2007. The meteorological inputs were maximum and minimum daily temperature, maximum and minimum daily humidity, and average wind speed. Latitude and longitude were supplied and the TEMP/W program used an energy balance approach to model the surface energy balance. To simulate the seabed temperature, a time dependent te mperature function was supplied as boundary condition, consisting of the average measured water temperature on 14 day basis. These are seen as crosses in the lower part of Figure 3.
No attempts were made to simulate the tidal fluctuation and its affect on the ground temperatures.

The model was run on two profile sections of different lengths and depths to both obtain detailed information on the near surface conditions, and impressions of the larger-scale ground temperatures in the coastal zone. The profiles were 92 m and 260 m long respectively and simplify a profile across the moraine and into Vallunden crossing Borehole 1.

Model results

Figure 5A shows a steady-state simulation for the immediate shore area. A high horizontal thermal gradient is seen in a narrow zone just below the shoreline. Since the mean annual water temperature is slightly below zero (-0.1°C), permafrost is modeled to be present in a thin layer below the seabed.

Figure 5B shows a snapshot plot from the transient model run from 7 April 2007. The sharp decrease of near surface temperatures reflects the winter freezing on land. A -1 °C isotherm has formed close below the seabed reflecting that the water temperatures approach -2°C during winter.

Figure 5C is a model run of the larger and deeper section but with the boundary conditions as those of Figure 5A. The pattern is similar as the one in Figure 5A but suggests that at depth, the presence of the sea will affect the ground thermal conditions more than 100 m from the shore, and similarly, that the cold temperatures from land will affect the sub-seabed temperatures at a similar distance offshore.

Figure 6 compares the measured and modeled temperatures in Borehole 1 for 7 April 2007. The discrepancy of model temperatures near the surface and towards the bottom is quite small, whereas the modeled temperature is up to 1.4°C wrong in the middle of the borehole. This and other snapshots throughout the year show that, while the general pattern is simulated reasonably well, there are discrepancies. These are often larger than those shown in Figure 6. However, the reasonable agreement of the modeled to the measured temperatures gives us some confidence in the general modeling results.

Discussion

The pronounced sill, Akseløya, restricts warm coastal water from entering Van Mijenfjorden and probably makes this fjord colder than other western Spitsbergen fjords. Sea ice cover is longer-lasting and more stable here. Therefore, this fjord is a primary candidate for possible subsea permafrost in western Spitsbergen fjords.

The modeling results of the subsea permafrost extend presented here should be seen as a minimum scenario. This is because the water temperatures were measured in a shallow, high-current strait, where the fjord water is strongly mixed with warmer fresh water during the summer. July temperature measurements from two deep basins in Van Mijenfjorden (Gulliksen et al. 1985) of -1.53°C and -1.27°C, respectively, indicate that water temperature in the deeper parts of the fjord remains below 0°C all year.

Permafrost, as defined solely on the basis of temperature, may not necessarily indicate cryotic subsea conditions. Sea water freezes at temperatures slightly above -2°C but capillarity and adsorption—in particular in fine-grained sediments—can further reduce the freezing point (Williams & Smith 1989). Thus, depending on the sediment properties, the seabed may well have permafrost by definition but still remain unfrozen. If the seabed consists of saline marine deposits, they will not be cryotic, even if thermally defined permafrost exists.

The 1300 A.D. surge of Paulabreen deposited lateral moraines in a rim around the inner parts of the fjord. A new detailed bathymetric survey indicates that glacial deposits also occupy the seabed here (Ottesen et al., in prep.). A seabed consisting of terrestrial sediments of glacial origin and with fresh rather than saline porewater could actually be frozen, but this hypothesis has not yet been tested.

The Crednermorenen moraine contains large amounts of buried glacier ice. It is possible that the unusual cold water conditions in Van Mijenfjorden are influencing the preservation potential of the ice-core in this moraine.

Conclusions

The permafrost temperatures measured in three boreholes in the ice-cored Crednermorenen moraine were studied for a period of a year. The surface temperatures in all holes were higher than the corresponding air temperature. The highest surface temperature was measured in Borehole 1 that normally has a snow cover of 20 cm while the two other boreholes are nearly snow free during winter. Most likely the warmer surface temperature in Borehole 1 is due to a surface offset (Smith & Riseborough 1996) caused by the insulating effect of snow.

Increasing temperatures were observed from the surface down through the active layer to the top of the permafrost in two of the boreholes. This is opposite to what would be expected if higher thermal conductivity of frozen ground compared to unfrozen ground causes an active layer (or thermal) offset. So this offset appears not to be important here; probably the ground is too dry.

Borehole 1 is located six m from the shore and is significantly warmer than two other boreholes both about 150 m away from the shoreline. To investigate the effect of the proximity to the sea, the finite element program TEMP/W was used to model the ground temperatures at the shore and below the seabed in both a steady-state and transient mode. Meteorological data and water temperature measurements were used to force the model.

The program manages reasonably well to simulate the ground temperatures in the near-shore borehole. The simulations indicate that permafrost, as defined solely on temperature, is present in a thin layer beneath the seabed of Van Mijenfjorden. Whether it is frozen or unfrozen will depend on the material properties.

At depth, the warming effect of the sea on the ground temperatures is modeled to penetrate more than 100 m inland and the cooling effect of land is affecting the seabed at an equal distance. The temperatures closer to the surface, however, are primarily locally controlled.

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