Svalbard airport runway. Performance during a climate-warming scenario.

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ABSTRACT: Svalbard airport runway (N78°14', E15°30') is constructed on continuous permafrost near the main settlement in the Svalbard archipelago, Longyearbyen. Since its completion in 1975, the runway has experienced pavement unevenness mainly caused by thaw subsidence (and consequent frost heave) of the ice-rich soil layers in the embankment. A major reconstruction of the runway was carried out in 1989, including insulation of the most affected areas. However, the reconstruction has only been partly successful and the runway is subjected to constant re-pavement with high maintenance costs. A new reconstruction is planned for 2005/2006 to improve the runway. The arctic region is expected to experience a mean annual temperature increase of between +4 °C to +7 °C during the next century and this may have a substantial impact for structures on permafrost. In order to evaluate the thermal performance of the runway under a climate change scenario, a final element model has been used to evaluate the thermal changes in the ground due to climate change.

KEY WORDS: Svalbard, airport, permafrost, climate change.

1 INTRODUCTION

Svalbard airport is situated approximately five kilometers northwest of Longyearbyen. The latitude is N78°14′ N, the longitude is E15°30′ E, and the altitude is between +21.3 and +28.6 a.m.s.l. The runway is built in an east-west direction, 2322 m long and 45 m wide (see Figure 1). A system of drainage ditches direct water from the mountain *Platåberget* through two large culverts that cross beneath the runway.

The airport was constructed during the summer seasons 1973 to 1975. Due to a lack of knowledge about permafrost engineering, site-specific climate, ground parameters and limited economical resources, a number of errors were made by the developers of the project (Instanes, D. and Instanes, A., 1998):

- Geotechnical investigation was not carried out prior to construction,
- Thermal analysis of the structure was not carried out prior to construction,
- The runway was cut into the ice-rich permafrost,
- Insulation of cut areas was not evaluated
- Use of geosynthetics was not evaluated,

- The criterion for the maximum depth of 0°C-isotherm was much too low (1100 mm)

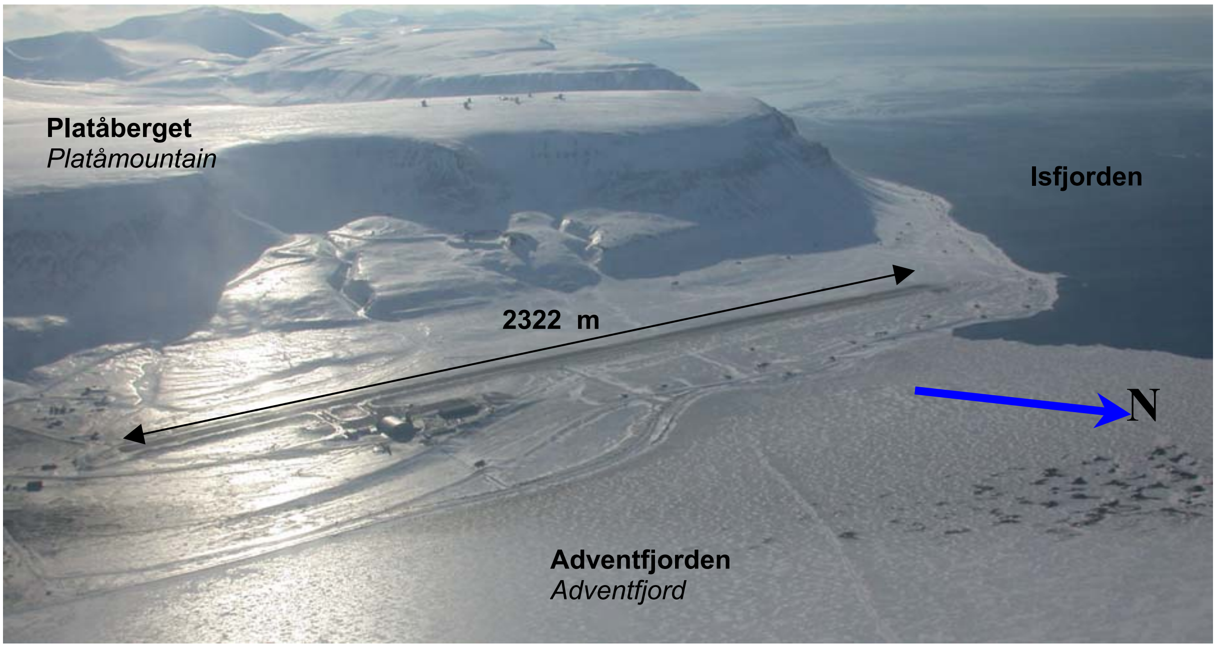

Figure 1: The runway at Svalbard airport

In order to reduce the volume of fill material required and consequently reduce costs, the developers decided that parts of the runway (approximately one third) should be cut into the terrain, while the remainder was elevated above the terrain on an embankment. From a permafrost engineering point of view, the decision to cut into the permafrost was unfortunate, since a ground thermal imbalance was introduced from the outset of the project.

At the time of construction, it was known that the native soil would not be able to support the load from the embankment in its thawed condition. A layer of frost stable fill was, therefore, placed on top of the native soil. The thickness of this layer varied from 1.1 m in parts of the cut sections to 4 m in the embankment area, but was not sufficient to prevent the native soils thawing during the summer months.

Due to the factors mentioned here, the runway experienced problems from the start in 1975. Thawing of ice-rich soil caused the runway to settle unevenly during the summer season. Re-freezing in autumn and winter created local frost heave. The result was a runway pavement where some points heaved 2 cm and adjacent points settled up to 3 cm during a single year (Strømner et al., 1998). The poor quality of the runway concerned the flight operators. Runway settlement depressions had to be filled with new asphalt on numerous occasions during the years following construction completion in 1975.

In 1989, a major reconstruction of the runway took place in which the most negatively affected reaches were insulated. The measure was relativly successful and further settlement/heave was halted in the newly insulated areas. The previously most troublesome parts of the runway became the most stable ones after the reconstruction. In a study initiated by the Norwegian Airport Authorities in 1995, insulation of the whole runway in a manner similar to the 1989 procedure was deemed the most favorable long-term runway maintenance strategy (Instanes, D. and Instanes, A., 1998). This has so far not been carried out, and a new reconstruction is planned for 2005/2006 to improve the runway.

The average global surface temperature is projected to increase from 1.4 to 5.8°C between 1990 and 2100 (IPCC, 2001). Warming at higher latitudes of the Northern hemisphere may be greater than the global average, as high as 4 to 7°C between 2000 and 2100 (ACIA, 2004). Climate warming may increase active layer depth and permafrost temperature and may act as an accelerator or catalyst for ongoing permafrost degradation associated with construction activity and existing infrastructure (Instanes, 2003). It was, therefore, of interest to investigate how climate warming may impact the runway at Svalbard airport.

2 CLIMATE AND GEOTECNICAL CONDITIONS

2.1 Climate

The climate in Svalbard archipelago is mild compared to other areas at the same latitude, mainly due to heat transport from lower latitudes performed by sea currents. Figure 2 shows the mean annual air temperature (MAAT) at Longyearbyen/Svalbard airport during the period 1912-2004. Monitoring of air temperature at Svalbard airport commenced in 1975. Data earlier than 1975 is from air temperature monitoring in Longyearbyen. It can be observed from the figure that there is a trend of increasing mean annual air temperatures during the last 20 to 30 years. However, the figure also shows that the area has previously experienced warm periods, especially 1920 to1940 and 1950s.

The mean annual air temperature at Svalbard airport during the period 1961-1990 was –6.7°C (Førland et al., 1997). During the period 1990-2004 the mean annual air temperature has increased to –5.1°C. Mean monthly air temperatures (MMAT) for the winter months can vary in excess of 20°C on a year-to-year basis while summers are much constant. Mean annual precipitation at Svalbard airport is 190 mm, which is the lowest value of any Norwegian meteorological station.

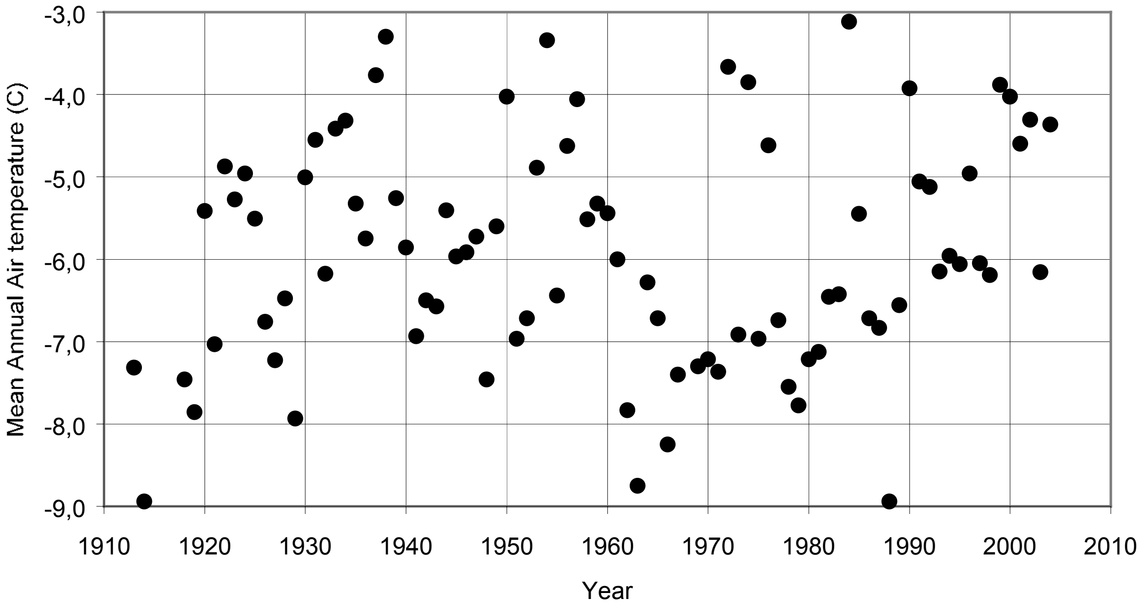

Figure 2: Mean annual air temperature (°C) at Longyearbyen/Svalbard airport 1912-2004

Svalbard airport is situated well within the continuous permafrost zone; the Longyearbyen area has a mean ground temperature of –6.0°C and an average permafrost thickness of about 240 m (Instanes, D. and Instanes, A., 1998).

2.2 Geotechnical conditions

A geotechnical survey was carried out in 1994 to evaluate the soil conditions at the site (EBA, 1994). Marine sediments, ranging from fine-grained silt to coarse gravel, underlie the airport. Some soil layers are described as very ice-rich and contain ice lenses up to 50 mm thick. At some locations beneath the runway, the soils have water contents as high as 75%. The soil profile shown in Figure 3 was found from the borehole in the insulated area,

Thaw subsidence and frost heave will not be a serious problem as long as the 0°-isotherm (thaw line) does not reach into the frost-susceptible ice-rich soil layers located from approximately 1.7 m depth beneath the surface. This means that the maximum active layer thickness for this soil profile must be less than 1.7 meters.

However, the ground temperature monitoring that was carried out in 1992-1995 showed that the active layer thickness in non-insulated areas was in excess of 2.5 meters (Instanes D. and Instanes, A., 1998). It was also reported that the surface temperature in the asphalt could reach +30°C on a sunny mid-summer day.

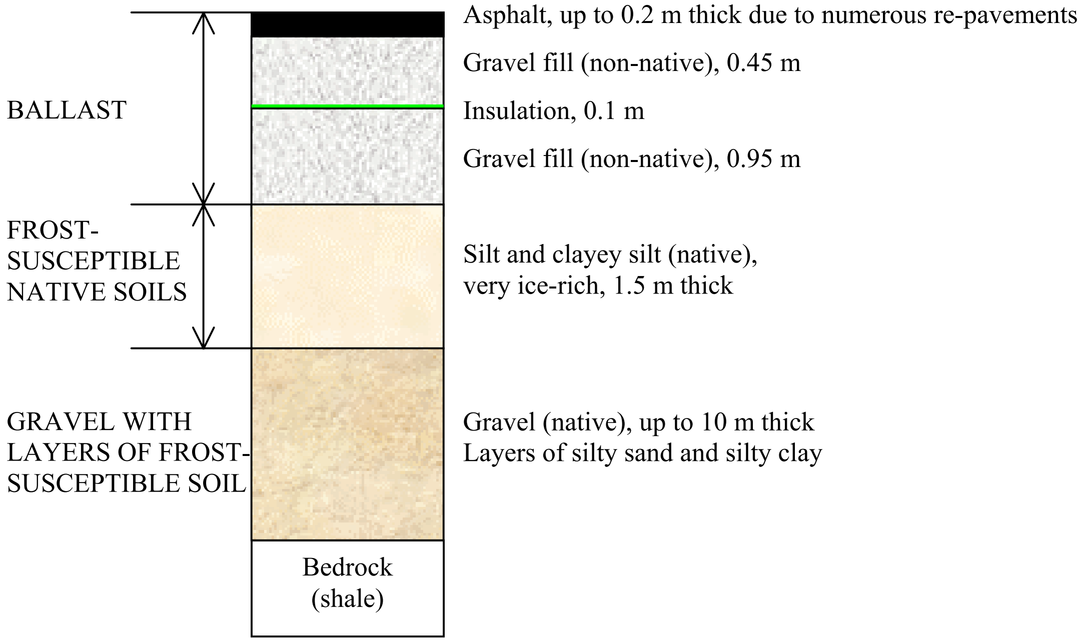

Figure 3: Soil profile insulated area

The strength and deformation characteristics of frozen soils are dependent on soil type, temperature, density, ice content, unfrozen water content, salinity, stress state and strain rate. Thawing of the frozen soil, or even an increase in the temperature of the frozen soil caused by construction activity or climate warming, may lead to deteriorating strength and deformation characteristics, potential accelerated settlements and possible foundation failure. Design of foundations in permafrost regions must, therefore, always include an evaluation of the maximum active layer thickness and permafrost temperature that the foundation soils will experience during the lifetime of the structure. The initial and long-term bearing capacity of the foundation can then be determined.

3 GROUND THERMAL ANALYSIS

3.1 Finite element model

In the analyses presented in this paper, the finite element software TEMP/W (GEO-SLOPE International Ltd., 2004) has been used to determine the thaw depth and permafrost temperatures for the runway embankment. The cross-section of the road embankment has been modelled using isoparametric 8-nodes quadrilateral or 6-nodes triangular finite elements. In addition, a 40 metre vertical profile of the embankment has been analysed one-dimensionally. The one-dimensional analysis is based on the assumption that the horizontal heat flow is negligible due to symmetry. The embankment was modelled according to the soil layers shown in Figure 3. The layers of silty clay and silt were treated as one layer of silty clay. The bedrock was assumed to be shale and was<encountered at 12 metres beneath the surface. The geotechnical survey did not give detailed information on mechanical and thermal properties for the different layers. Representative values for volumetric water content, density, degree of saturation, unfrozen water content, thermal conductivity, heat capacity and latent heat was, therefore, chosen based on the available information (grain size distribution and water content).

3.2 Air temperature input data

Mean monthly air temperatures from the historical record 1912-2000 and predicted mean monthly air temperatures 2000-2050 from empirical downscaling of the Max Planck Institute's ENCHAM4 GCM climate model (Hanssen-Bauer et al., 2000), was then applied in the thermal analysis to estimate thaw depth and permafrost temperatures for the modelled theoretical embankment 1930-2050. Figures 4 and 5 show the variation in air thawing index and air freezing index and Longyearbyen/Svalbard airport 1912-2050 based on observations (historical data) and the climate model. The air thawing index (ATI) and air freezing index (AFI) are useful parameters to determine thaw depth and permafrost temperatures. ATI is defined as the integral of the sinusoidal air temperature variation during one year for T > 0°C (the air freezing index, AFI, is defined as the integral of the sinusoidal air temperature variation during one year for T < 0°C) (Instanes, 2003).

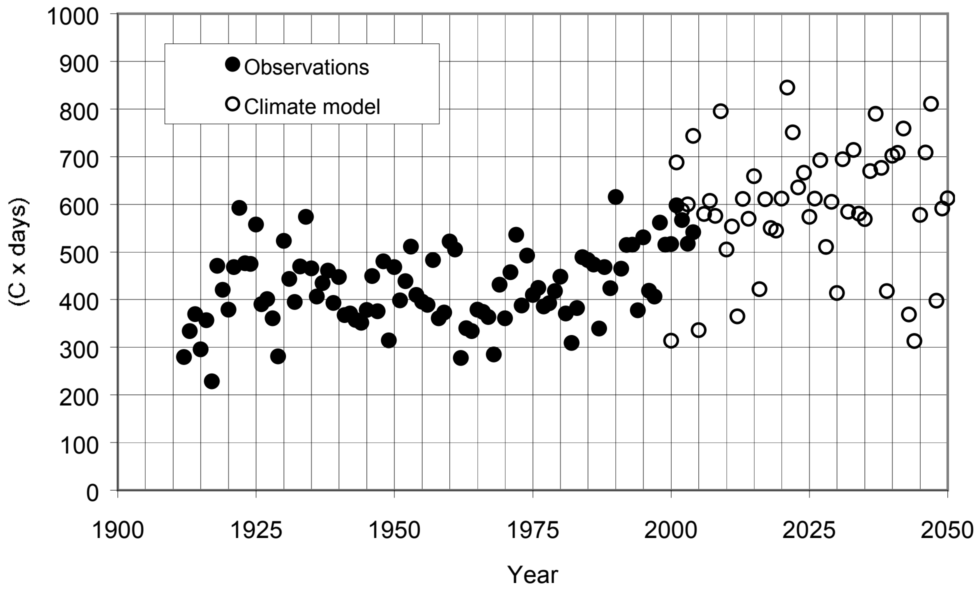

Figure 4: Air thawing index (°C·days) Longyearbyen/Svalbard airport 1912-2050

It can be observed from Figure 4 that the air thawing index decreased from 1925 to 1970 (cooling summers) and increased from 1970 to 2004 (warming summers). The climate model shows a significant increase during the next 50 years. The historical maximum air thawing index for Longyearbyen is 615ºC·days observed in 1990. This value is likely to be exceeded in 38% of the summers in the period 2000 to 2050 based on the climate model presented above. The extreme values exceed 800ºC·days.

From Figure 5 it can be observed that the air freezing index has decreased from 1912 to 1940 (warming winters), increased from 1940 to 1970 (cooling winters) and decreased from 1970 to 2002 (warming winters). However, the period from 1970 to 2004 is still not as warm as the period from 1925 to 1955. The climate models show a significant decrease in air freezing index (warming winters) during the next 50 years. The historical minimum air freezing index for Longyearbyen is 1485ºC·days observed in 1954. Based on empirical downscaling, 26% of the winters are likely to be warmer than the historical minimum in the period 2000 to 2050. The extreme warm winter has an air freezing index below 1000ºC·days (Instanes, 2003).

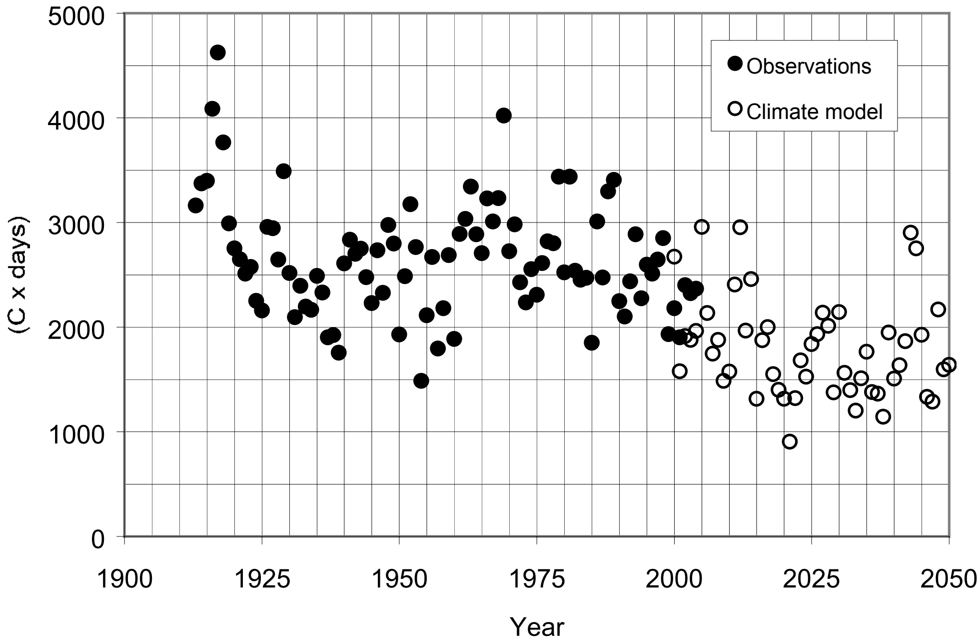

Figure 5: Air freezing index (°C·days) Longyearbyen/Svalbard airport 1912-2004

4 RESULTS

Initial thermal analyses were performed to evaluate if the model was capable of reproducing recorded ground temperatures which were recorded during the summer and autumn of 1994. Detailed ground temperature data was available for this time period. Figure 6 shows one example of how the modeled temperature profiles compare to values measured during that time period. It can be observed from Figure 6 that the model gives a good representation of measured temperatures.

Maximum thaw depths (modeled) generally occur between August 15 and September 15. Rapid freeze-back of the soil profile takes place in October.

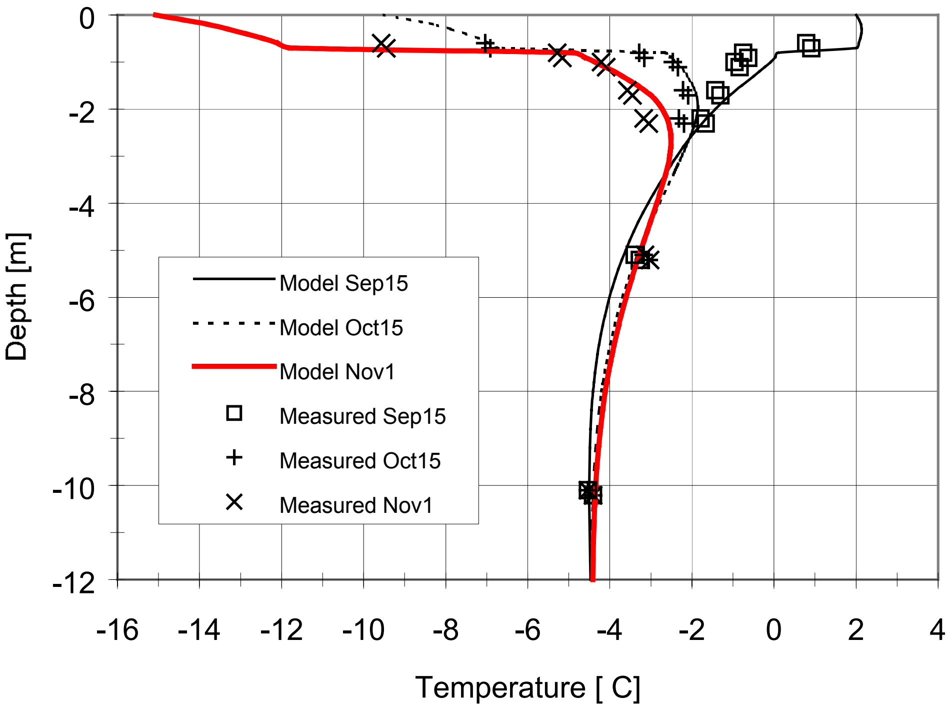

Figure 6: Modeled ground temperatures compared to measured values, September to November 1994.

Figure 7 shows the calculated theoretical maximum thaw depths for the insulated part of the runway. To enable a historical comparison, thaw depth values from 1930 and onwards are presented. As the runway was finished in 1975 and not insulated until 1989, thaw depth values prior to 1990 are purely theoretical.

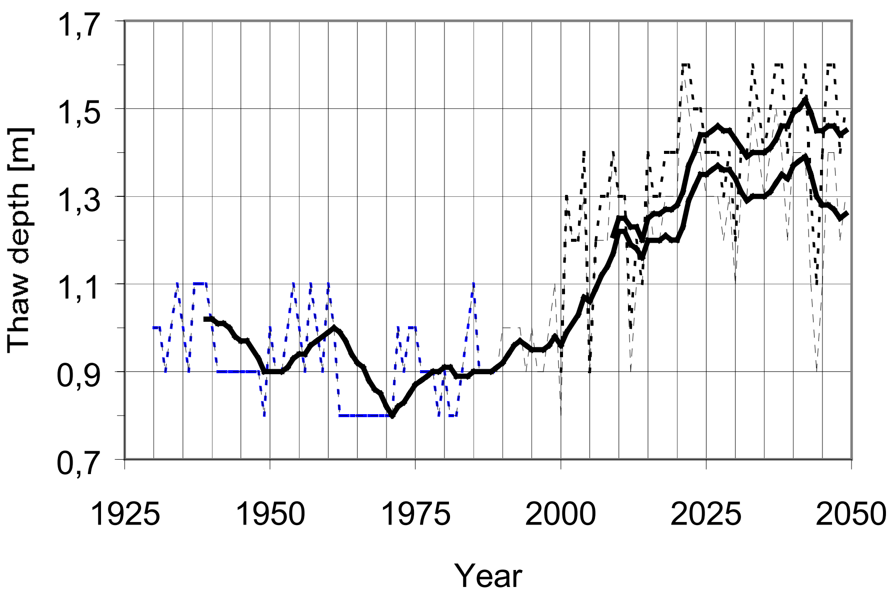

Figure 7: Modeled thaw depth.

Dashed line 1930-1990: Thaw depth based on observed mean monthly air temperature data

Dashed line 1990-2050: Thaw depth based on observed and climate model mean monthly air temperature data

Solid line 1930-2050: Thaw depth based on 10-year running average of observed and climate model mean monthly air temperature data. The upper curve 2010-2050 has an additional warming of 0.3ºC/decade added to the input data

As can be seen from Figure 7, average thaw depths can be expected to increase by as much as 0.5 m during the first half of the 21st century compared to the (theoretical) level during the latter half of the 20th century. The average thaw depth increases from about 0.9 m to approximately 1.35 m. The maximum thaw depth (modeled) during the 1950 to 1999 time period is 1.1 m, which has increased to 1.6 m for the 2000 to 2049 period. The upper solid line in Figure 7 is an example of the sensitivity of the thaw depth to uncertainties in climatic input data. The upper solid line is a running average based on the empirically downscaled data but with the addition of a 0.3°C / decade warming trend added to the data. As can be seen from the figure, the result of the strong additional warming is an increase in thaw depth by the moderate amount of 0.15 m (mid-21st century). It appears that site conditions at Svalbard airport are currently such that the thaw depth response to a temperature increase is approximately linear, something that is not always the case. Strong non-linear relationships between thaw depth and temperature can occur when discontinuous permafrost experiences a warming climate (Mjureke, 2001).

Figure 8 shows how the ground temperature at certain depths changes over time. As can be seen, March-temperatures at the 2 m level show the strongest warming trend during the first half of the 21st century, approximately +4°C. September-temperatures increase by only +1°C at the same depth during the same time period. The strong positive trend in March-temperatures at 2 m depth partly reflects the fact that air temperature warming is predicted to be stronger wintertime than summertime in the climate scenario used in this study. The weak trend in September-temperatures at the 2 m depth is to a large extent explained by the proximity of the 0°C-isotherm and associated phase change. A higher energy input resulting from higher air temperatures causes the thaw line to penetrate deeper rather than to warm the soil below. At a shorter time scale, large March fluctuations in temperature reflect variable winter conditions while summers are more uniform. From approximately 10 m depth and downwards, seasonal temperature variations within the single year are small. At 40 m depth (negligible intra-annual variation), temperatures increase by approximately +2°C between year 2000 and 2050.

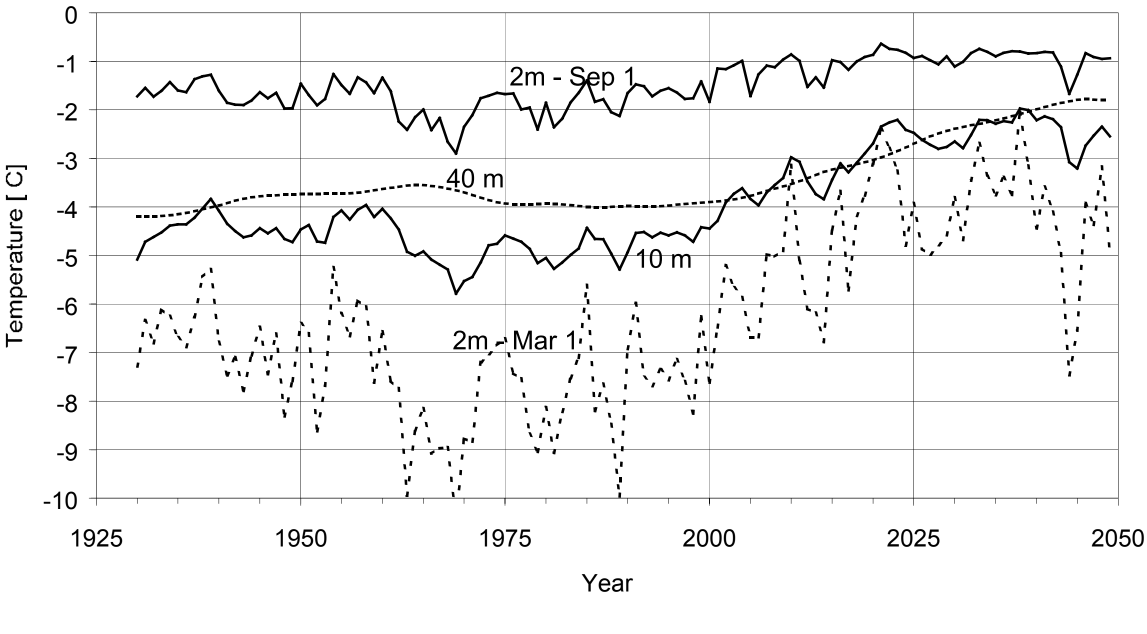

Figure 8: Ground temperature at 2 m, 10 m and 40 m depth.

5 SUMMARY AND CONCUSIONS

This paper has presented the possible impact of climate warming on the thaw depth and permafrost temperatures for the runway of Svalbard airport, Longyearbyen. From an airport management point of view, the increase in thaw depth predicted by the model is not necessarily alarming. The thaw line does not reach the thaw sensitive soil layers, situated between 1.7 and 3.2 m depth, although the margin gets dangerously narrow only two decades into the 21st century.

The design lifetime for structures in permafrost regions is typically 30 to 50 years. Within this timeframe the structure should function according to design with normal maintenance costs. Total rehabilitation, demolition and replacement of old structures must be expected and are part of sensible infrastructure planning and engineering practice.

Based on the results from this study, it is believed that the climate scenarios do not pose an immediate threat to the runway at Svalbard airport. Compared to today's situation, maintenance cost will probably increase, but it is possible to gradually adjust the runway to a warmer climate by applying insulation or with more frequent maintenance.

The 2005-2006 reconstruction will be carried out based on a best value for money approach. This means that higher maintenance costs may be the preferred solution compared to the higher initial re-construction costs involved in the replacement of frost-susceptible soils and insulation.

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