Heat Transport and the Effects of Climate Change in a Large-scale Waste Rock Pile Located in a Continuous Permafrost Region at Diavik Diamond Mine

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Abstract

An on-going field study at the Diavik Diamond Mine, NT, Canada, is examining the hydrology, geochemistry, microbiology, gas transport, and heat transport mechanisms controlling acid rock drainage (ARD) in low sulphide waste rock the Canadian Arctic. The mine is located in the zone of continuous permafrost. This paper is focused on the thermal behaviour within a large-scale waste rock pile. Three drill holes to 40 m depth were used to monitor temperature inside the waste rock pile, beginning in July 2010. Temperatures measured at 5 m spacing indicate that the 0 °C isotherm is currently at 11 m below the top of the pile, reflecting thermal conditions following pile construction. Temperature variations in these drill holes are controlled by conductive heat transfer. Conduction modeling predicts that, with climate change, the 0 °C isotherm will be located at 7 m depth in 2110. Placement of a near-saturated till layer over the waste rock is predicted to cause the 0 °C isotherm only penetrate to 3.9 m in 2110.

Key Words: acidic drainage, permafrost, active layer, thermal modeling

Introduction

An on-going field study at the Diavik Diamond Mine, NT, Canada, is examining the hydrology, geochemistry, microbiology, gas transport, and heat transport mechanisms controlling acid rock drainage (ARD) in low sulphide waste rock located in the Canadian Arctic. At the end of the mine life, up to 120 Million tonnes (Mt) of waste rock will be stockpiled in a 60 to 80 m high permanent pile covering 3.5 km^2. The waste rock excavated during operations is analyzed for sulfur content and segregated into Type I (<0.04 wt % S), Type II (0.04 to 0.08 wt % S) or Type III (>0.08 wt % S) and stored in separate areas within the waste dump. Dry Engineered covers are a closure concept for the Type II and Type III waste rock dumps, including re-sloping the Type III areas to 18.4° (3H:1V) and covering with a 1.5 m lower permeability layer of till, and a 3 m layer Type I waste rock to act as an active freeze-thaw layer (Smith, 2009).

To monitor the evolution of thermal, geochemical and hydrogeological processes within the waste rock dump, three 8-inch holes spaced at 5 m, FD1 (32.2 m depth), FD2 (30.7 m depth) and FD3 (40.2 m depth), were drilled in May 2010 to install instruments. The instruments include thermistor cables, gas lines, soil water suction samplings (SWSS), ECH$_2$O moisture content sensors and permeability balls (Figure1). The drill holes were back filled with 3/4 inch crush and silica filter sand. Thermistors were installed at 5 m vertical spacing and ground temperatures are recorded at a 12-h interval. Hourly air temperature is measured at the Diavik meteorological station, which is about 1 km from the waste rock dumps.

This paper presents measured temperatures from installed thermistor cables in the waste rock dump. In 2011, additional boreholes were instrumented in other locations within the waste dump, but these data are currently being processed. Numerical simulations were carried out for a cover system based on the closure concept of the waste dump and for an uncovered waste rock pile to examine the thermal evolution into the future and the role of long-term climate change. The results of the simulations show the significant of the predicted future climate on the depth of the 0 °C isotherm in the waste dump and permafrost ground temperatures.

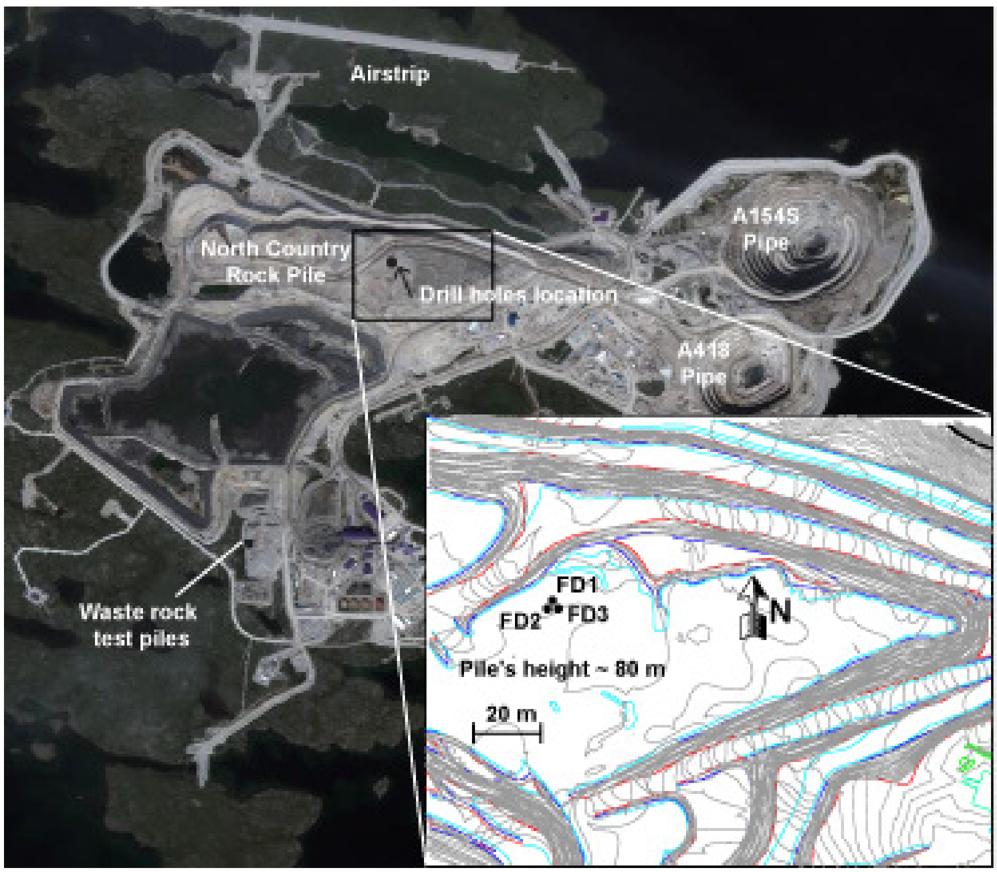

Figure1: Diavik Diamond Mine site map with location of the drill holes

Experimental Results and climate change

Air temperatures

Monthly averaged air temperatures vary significantly throughout the year, with the warmest temperatures in July and coldest in January. Indeed, over a ten-year period (from 2000 to 2010), monthly averaged air temperature in January and July was -29.3 °C and 11.5 °C, respectively (Figure 2A). Daily averaged air temperatures also varied significantly, however they showed greater fluctuation in winter (peak in January) than in summer (peak in July). It can be noted that the daily average air temperatures were -43 °C on January 21, 2002 and -5.2°C on January 19, 2009, and varied between 22.3 °C on July 27, 2003 and 4.8 °C on July 2, 2003 (Figure 2A).

The ground surface temperature variations are controlled by the local variation in air temperatures, precipitation, wind speed, solar radiation, among other factors (Frauenfeld et al., 2007). Air freezing and thawing indices, I_{af} (°C-days) and I_{at} (°C-days), which are used in describing the intensity of air-temperature variations, were calculated using Equation 1 and 2 in which t is time and T is air temperature in °C. Over the measured period, the averaged value of I_{af} was -4426.3 °C-days and the averaged value of I_{at} was 1082.7 °C-days. A linear trend line shows both I_{af} and I_{at} have increased over this 10-year period (Figure 2B). In fact, the thawing-index trend line indicates that I_{at} has increased 36 °C-days/decade (between 2000 and 2010) whereas the freezing-index trend line shows I_{af} has increased about 120 °C-days/decade. Frauenfeld et al. (2007), who analyzed air temperature data for various Northern Hemisphere land regions at latitudes north of 50 °N for recent decades, found the freezing index has increased on average by 85.6 °C-days/decade while thawing index has increased by 44.4 °C-days/decade. The differences in the rates (both I_{af} and I_{at}) between this study and Frauenfeld et al. (2007) could reflect the shorter length of the period of available data to determine the rates (a decade versus three decades) and/or local variations.

$$I_{atf} = \int_{t_o}^{t_1} T \mathrm{d}t \qquad T < 0°C \qquad \text{(Equation 1)}$$

$$I_{at} = \int_{t_o}^{t_1} T \mathrm{d}t \qquad T > 0°C \qquad \text{(Equation 2)}$$

Average mean annual air temperature (MAAT) was -9.1 °C over the decade and the trend line indicates an increasing rate of 0.73 °C/decade (Figure 2C). Figure 2C also shows that in 2004 air temperature was significantly colder than MAAT at -12.1 °C, whereas in the years 2006 and 2010 MAATs were much warmer at -6.4 °C and -6.7 °C, respectively. Chylek et al. (2009) determined long term air temperature trends (between 1880 and 2008) for the low Arctic (64 °N - 70 °N). They found three distinct periods: strong warming periods between 1880 - 1940 and 1970 - 2008 with warming rate of 0.59 °C/decade and 0.38 °C/decade, respectively, separated by a cooling period between 1940 and 1970 with a cooling rate of -0.36 °C/decade. Again, the difference in warming between this study and Chylek et al. (2009) reflects the length of the analysis and local fluctuations. The warming of air temperatures can also be associated with an increase in thawing days and a decrease in freezing days. Averaged thawing and freezing days were 122.4 days and 242.9 days. The number of thawing days has increased 5.7 days/decade and the number of freezing days has decreased 6.0 days/decade over the period based on available data (Figure 3).

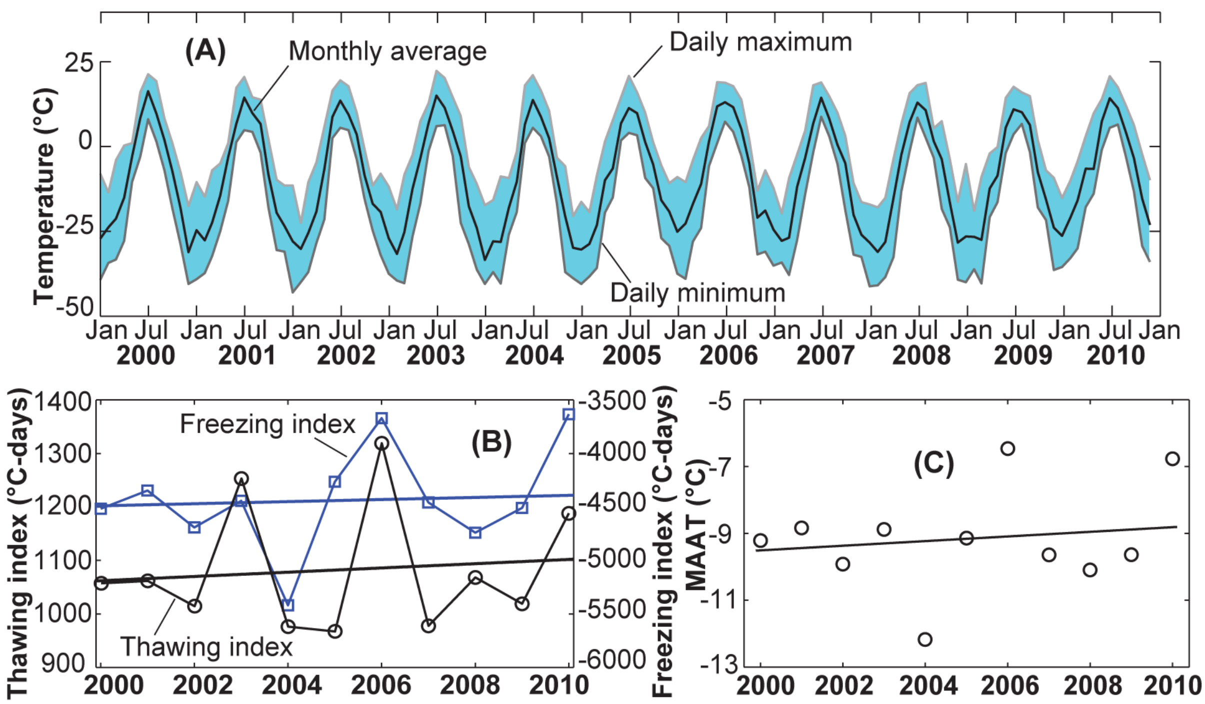

Figure 2. Monthly averaged air temperatures plotted with daily maximum and minimum air temperatures(A), calculated air thawing and freezing indices based on daily averages (B) and calculated mean annual air temperate (MAAT) (C). Data from Diavik Mine weather station.

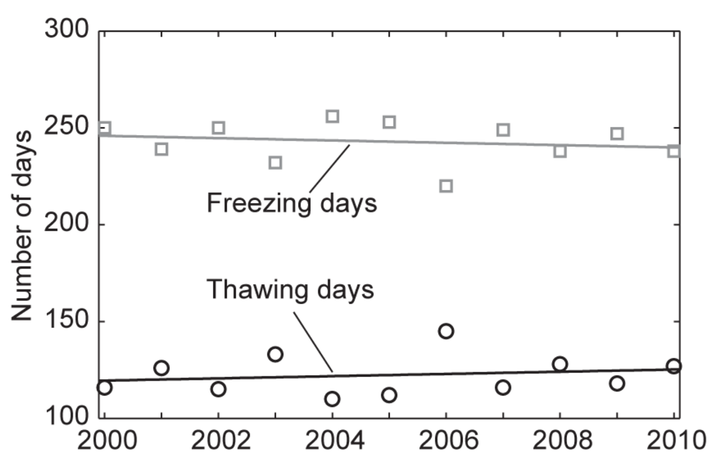

Figure 3. A variation of thawing and freezing days of air temperatures

Ground Temperatures

Ground temperatures below the surface of the waste rock pile can be represented using periodic functions obtained using Fourier analysis. The following is such an expression used to describe temperature as a function of time:

$$T(y,t) = a_0 + \sum_{1}^{n} \left(a_i \cos(i\omega t) + b_i \sin(i\omega t) \right) \qquad \text{(Equation 3)}$$

Where a_0 represents the mean annual ground temperature (MAGT) at a specific depth y, ω is the fundamental angular frequency. $A_i = (a_i^2 + b_i^2)^{1/2}$ and $\phi_i = \arctan(a_i/b_i)$ are amplitude and phase of ground temperatures corresponding to angular frequency iω. For representing ground temperatures, the value n =2 is sufficient (Tan and Ritchie, 1997).

Under assumptions of a periodically varying ground surface temperature and one-dimensional conductive heat transfer, the apparent (effective) thermal diffusivity (κ) can be calculated using phase or amplitude equations:

- Phase equation

$$\kappa = \frac{1}{2\omega}\left(\frac{y_2 - y_1}{\delta t}\right)^2 \qquad \text{(Equation 4)}$$

- Amplitude equation

$$\kappa = \frac{\omega}{2}\left(\frac{y_2 - y_1}{\ln\left(\frac{|T_2|}{|T_1|}\right)}\right)^2 \qquad \text{(Equation 5)}$$

Where: δt is phase difference, T_1 and T_2 are temperature amplitude at two depths y_1 and y_2. The values of Fourier's coefficients are shown in Table 1 at selected depths and the periodic functions described by Equation 3 with the calculated coefficients are plotted in Figure 4. The Fourier-series curves fit the monthly averaged ground temperatures very well. Furthermore, the ground surface temperatures were measured within 1 cm of the waste pile surface, which show the mean annual surface temperature (MAST) of -6.3 °C and amplitude of 20.5 °C. The amplitudes of ground temperature variations reduced rapidly with depth from 20.36 °C at the surface to 0.14 °C at 14.50 m depth (Table 1).

Table 1. Calculated Fourier's coefficients with ω=2π/365

Depths (m)	a_0	a_1	b_1	a_2	b_2	A_1
Borehole FD1						
Surface	-6.30	18.89	7.60	1.03	-0.14	20.36
1.86	-2.19	-4.60	-9.02	0.43	1.03	10.13
6.86	-0.97	0.75	-2.9	-0.10	0.63	3.00
11.86	-0.56	0.72	-0.20	-0.33	0.21	0.75
16.86	-0.05	0.01	0.01	-0.04	-0.02	0.01
Borehole FD2						
Surface	-6.36	-18.90	-8.20	1.76	-0.51	20.60
0.66	-4.80	-11.18	-10.16	1.50	-0.15	15.11
5.66	-1.08	0.73	-4.18	-0.16	0.56	4.24
10.66	-1.01	0.92	-0.54	-0.19	0.38	1.07

Borehole FD3						
4.50	-0.22	0.16	-3.33	-0.58	1.14	3.33
9.50	-0.67	0.71	-1.02	-0.33	0.67	1.24
14.50	-0.13	0.14	0.03	-0.08	-0.04	0.14
19.50	-0.32	0.00	-0.07	0.02	-0.03	0.07

Based on monthly averages, temperature profiles at FD1, FD2 and FD3 show the depth of the 0 °C isotherm at 11.5, 10.0 and 12.5 m, respectively (Figure 5). The depth of the 0 °C isotherm is expected to change over time as it evolves toward an equilibrium profile following pile construction, and the superimposed effect of global climate change. From December to April, and from the surface to the borehole depth of 40 m, ground temperatures were below 0 °C. The other months the upper zone of the waste dump was above 0 °C. The measured ground temperatures have not shown significant increase in temperature associated with oxidation of sulphide minerals at any depth when the overall temperature trend is examined.

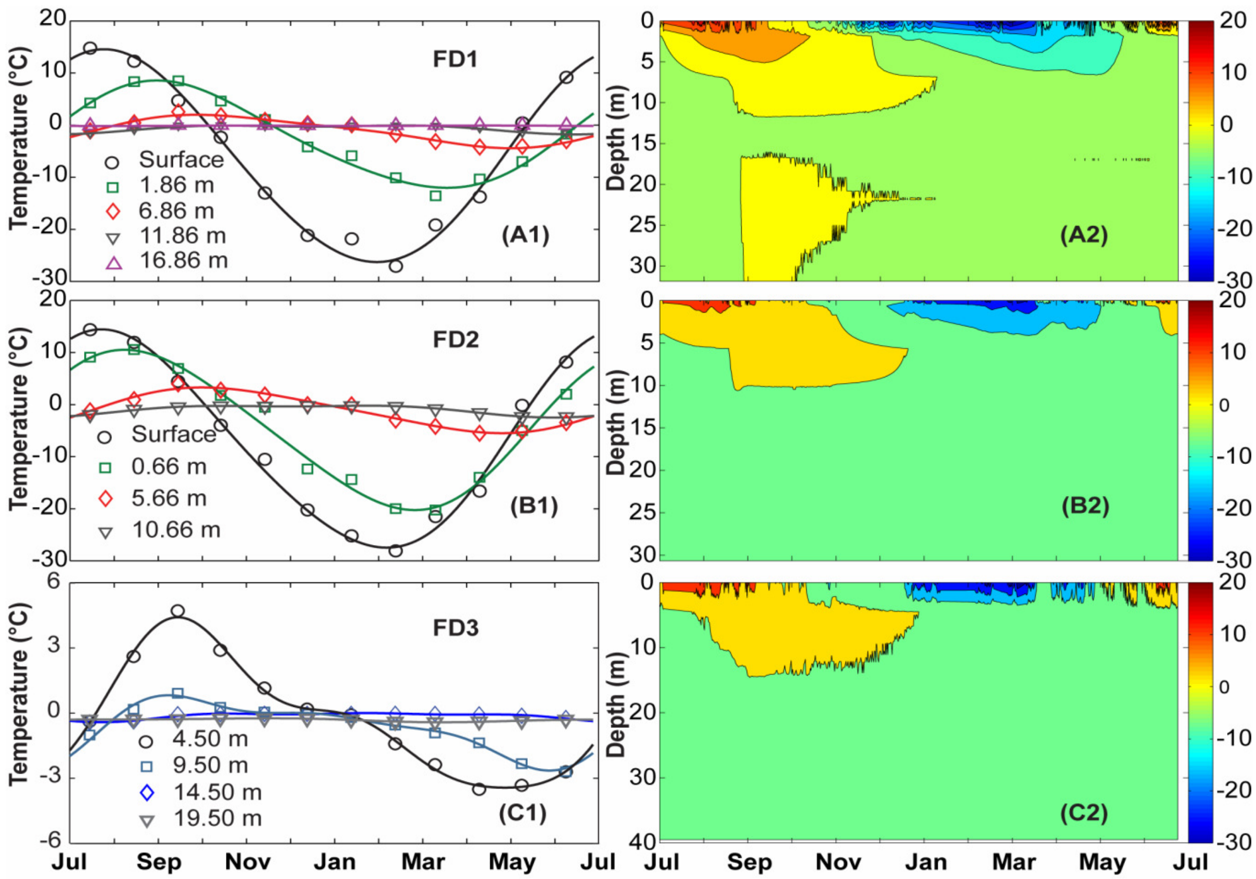

Figure 4. Monthly averaged ground temperatures from July 2010 to July 2011 at selected depths of FD1 (A1), FD2 (B1) and FD3 (C1); time-temperature-depth plot of FD1 (A2), FD2 (B2) and FD3 (C2).

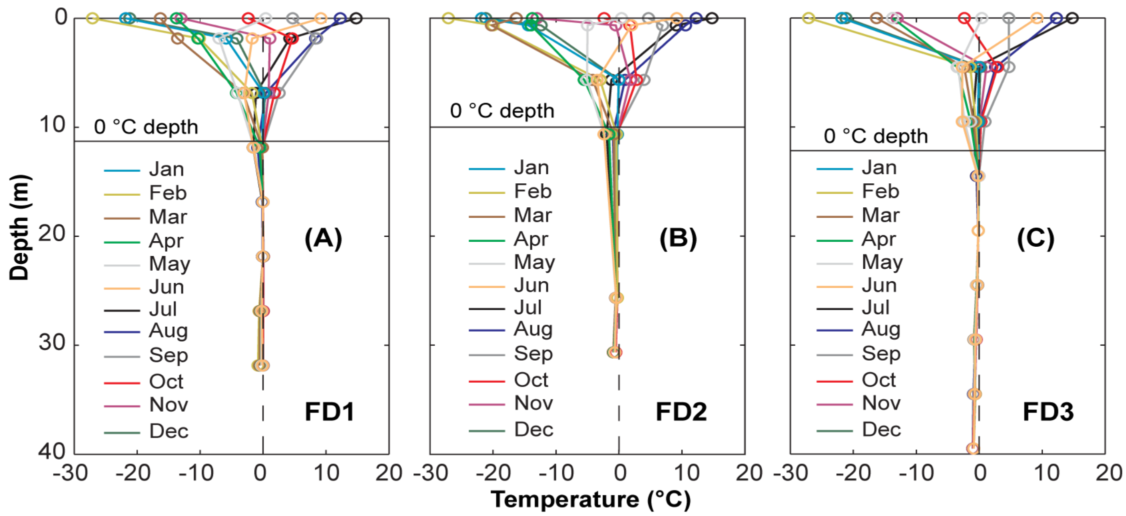

Figure 5. Temperature profiles of FD1 (A), FD2 (B) and FD3 (C)

The relation of the amplitude ratios between surface temperature and ground temperatures at depths were fitted well using an exponential curve with $R^2 = 0.96$ (Figure 6A). A linear regression was used to fit the relation between phase delay with depths to 14.50 m (Figure 6B) $R^2 = 0.97$ and below 14.5 m ground temperatures were strongly attenuated, as indicated by points that did not follow the linear regression line. An exponential curve was used to fit the relation between amplitude ratios and phase delays with $R^2 = 0.95$ (Figure 6C) for those ground temperatures to 14.5 m depth. The curves shown in Figure 6 indicate that heat transfer by conduction dominates in the waste dump and bulk thermal diffusivities were determined to be 5.39×10^{-7} m²/s (Equation 5) and 8.49×10^{-7} m²/s (Equation 4) and with an average of 6.94×10^{-7} m²/s. The average bulk thermal diffusivity is comparable to the value of 7.96×10^{-7} m²/s of a 15-m high experimental waste rock pile at the Diavik site (the Type I test pile; Pham et al., 2011).

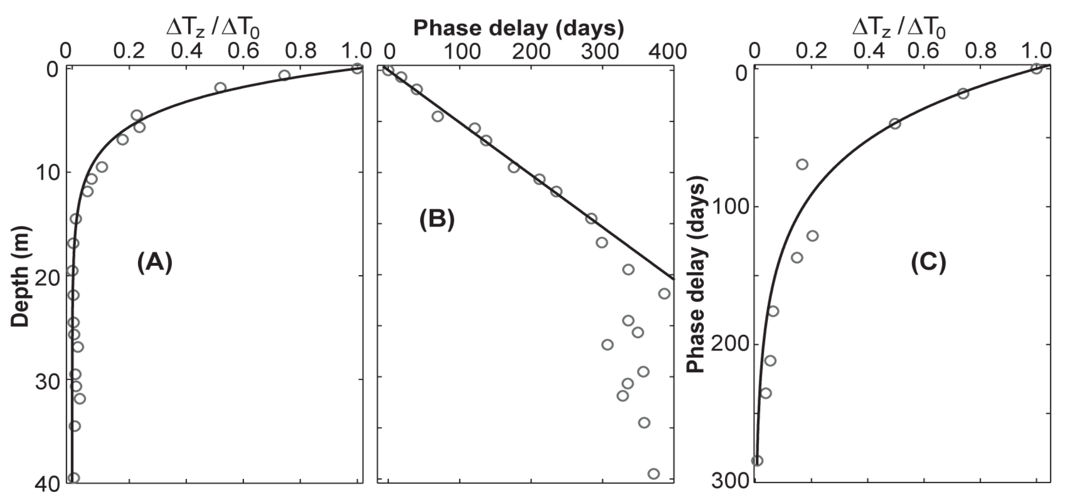

Figure 6. Relation between depth and amplitude ratio (A); depth and phase delay (C); phase delay and amplitude ratio (C)

Modeling Climate change

The climate models were run in two sets of six model members, one set to simulate the historical climate of the earth, and the other set was to simulate the future climate using up-to-date data adjustment (available up to early 2007) corresponding to the IPCC's A2 scenario (Nakicenovic and Swart, 2000). This makes the prediction closely resemble the A1B greenhouse gas/aerosol forcing scenario. The predictions of minimum, mean, and maximum temperatures from the assembled mean climate model were compared to those observed at Environment Canada's weather stations at Lupin A and Ekati and the limited data from the Diavik mine site for the period through to 2007. The predictions of annual temperature rise from 1970 to 2060 and are shown in detail in Figure 7:

- Maxima: from -8.3 °C to -2.8 °C, a rise of 5.5 °C over the 90 year period or 0.061 °C/year.
- Mean: from -11.0 °C to -6.0 °C, a rise of 5.0 °C over the 90-year period or 0.056 °C/year.
- Minima: from -14.7 °C to -9.3 °C, a rise of 5.4 °C over the 90-year period or 0.060 °C/year.

The predicted annual temperatures show a relatively constant rate of temperature increase over the period. The predicted-mean annual temperatures match closely to the measured MAATs although there were some years when the measured MAATs was closer to the predicted minimum or maximum, as expected (Figure 7A). Warming rates for months in the transitions between the four seasons are shown in Table 2. In January, the warming trends are quite significant for both the minima and maxima, which are the largest warming rates, and the warming rate of minima temperatures are slightly higher (Table 2 and Figure 7B). The warming rates in April and October are similar and quite comparable to the mean-annual warming rates, whereas the warming rates in July are the smallest (Table 2). In Figure 7A, the predicted minimum and maximum annual temperatures are the predictions of coldest and warmest climate models. The predicted mean annual temperatures are the mean of the predicted minimum and maximum annual temperatures.

Table 2. Predicted future air temperatures for selected months at Diavik.

	Maxima		Mean		Minima	
	1970 2060 (°C)	Rate (°C $year^{-1}$)	1970 2060 (°C)	Rate (°C $year^{-1}$)	1970 2060 (°C)	Rate (°C $year^{-1}$)
January	-27.4 -19.8	0.084	-30.3 -22.6	0.086	-33.6 -25.4	0.091
April	-11.5 -7.9	0.040	-15.7 -11.0	0.052	-19.3 -13.7	0.062
July	15.7 17.5	0.020	11.6 13.7	0.023	7.5 9.4	0.021
October	-4.8 -0.6	0.047	-7.4 -2.5	0.054	-9.9 -4.4	0.061

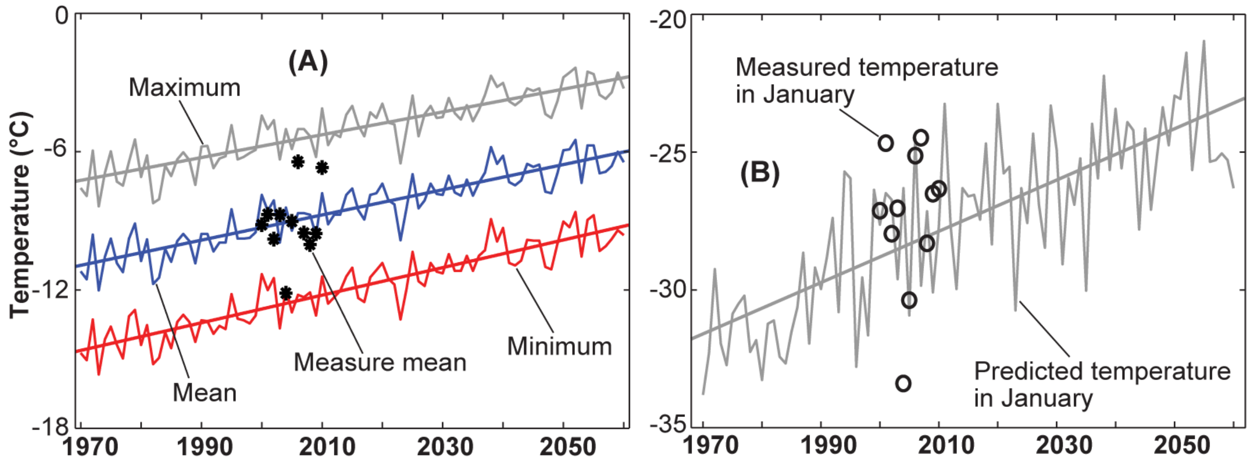

Figure 7. Predicted minimum, mean and maximum annual temperatures (A) and predicted mean January temperatures (B) for Diavik

Numerical simulation of heat transfer of the waste dump with climate change

Simulation cases

Predictions of future temperatures within the waste dump are derived from a one-dimensional conduction model. Case 1 is the baseline case, in which no cover layer is placed on top of the Type III waste rock. The pile is assigned a thickness of 80m. The case is used to investigate the change in depth of the 0 °C isotherm and ground temperatures under the future climate. Case 2 is a closure concept, where the Type III waste rock is capped using a 1.5 m till overlain with 3 m of Type I waste rock. Boundary conditions for Cases 1 and 2 are no heat flux at bottom of Type III waste dump. No heat flux at the bottom is used for preliminary investigations due to lack of measurements. This can be justified due to the boundary being at a great depth to the surface (80 m) and/or a low thermal conductivity liner at the base. The surface temperature is

$$T_s = -6.3 + 20.3\sin\left(\frac{2\pi t}{365}\right) + \frac{0.056t}{365} \quad \text{(Equation 6)}$$

With climate change of 0.056 °C/year at the surface, and initial temperatures resembling measured temperatures on July 2010 using the instrumented boreholes.

Material properties

Thermal properties of the Type I, Type III waste rock and till were determined using *in situ* measurements from three experimental waste rock piles at the Diavik mine site, and calculated from measured ground temperatures within each same materials (Table 3) (Pham et al., 2011). Volumetric moisture contents of the Type I and Type III waste rock are assumed to remain at field capacity, about 5.7%, which was measured in the field due to the low precipitation and high evaporation at Diavik (Neuner, 2009).

Table 3. Material properties for materials used in simulation

Property	Value
Type I waste rock	
Porosity	0.25
Thermal conductivity	1.65 W/m/K
Frozen bulk heat capacity	2.38×10^6 J/m^3/K
Thawed bulk heat capacity	2.40×10^6 J/m^3/K
Volumetric water content	0.057
Type III waste rock	
Porosity	0.25
Thermal conductivity	1.69 W/m/K
Frozen bulk heat capacity	2.13×10^6 J/m^3/K
Thawed bulk heat capacity	2.15×10^6 J/m^3/K
Volumetric water content	0.057
Till	
Porosity	0.2
Frozen thermal conductivity	3.20 W/m/K
Thawed thermal conductivity	2.90 W/m/K
Frozen bulk heat capacity	2.13×10^6 J/m^3/K
Thawed bulk heat capacity	2.51×10^6 J/m^3/K
Volumetric water content	0.18

Results

The simulation cases were run for 100 years from July 2010. The assigned mean surface temperature T_s, after 100 years, at the top of the 80 m waste rock dump, will be -0.7 °C, which is similar to the current MAST at Yellowknife, Northwest Territories, Canada which is in the zone of discontinuous permafrost (Heginbottom et al., 1995).

Case 1

From measured data between July 2010 and July 2011, the 0 °C isotherm is initially about 11 m below the top surface and it rapidly rises to 3.9 m in 2014. From 2014 to 2020, the 0 °C isotherm slowly rises to a depth of 3.7 m, which is the minimum depth to reach 0 °C. After 2020, the 0 °C isotherm gradually moves downward with an average rate of 3.6×10^{-2} m/year (or 3.6 cm/year) to 7.0 m in 2110 (Figure 8A). At 4 m depth, ground temperature varies significantly with an amplitude of around 10 °C. Initially it decreases until 2020 similarly to the 0 °C isotherm and then increases. Its maximum value reaches 0 °C and 3.5 °C in 2040 and 2110, respectively. Meanwhile its minimum value is -10 °C in 2020 and increases to -6 °C in 2110. The temperature amplitude at 7 m is smaller (about 3 °C) and its maximum temperature does not reach 0 °C until 2110 (Figure 8B).

Below 20 m, the amplitude of the annual ground temperature variations are small and can be negligible. At 20 m, waste rock temperatures reach a minimum value of -3.4 °C in 2040 and then gradually increases to a value of -1.6 °C in 2110. The initial decrease is due to the initial temperature at 20 m, which is lower than the MAST and the later increases are due to the warming of MAST. The greater the depth below the surface, the later temperatures reach their minimum before gradually increasing (Figure 8C). This reflects the influence of warming and conduction behavior of the waste dump. Moreover, the waste rock acts as a low-pass filter of the temperature signal by removing short-term fluctuations (high frequencies) and leaving long term trends (long-term climate change). Figure 8D shows by 2110, the surface temperatures fluctuate between -21.0 and 19.6 °C and the 0 °C isotherm is at 7 m depth.

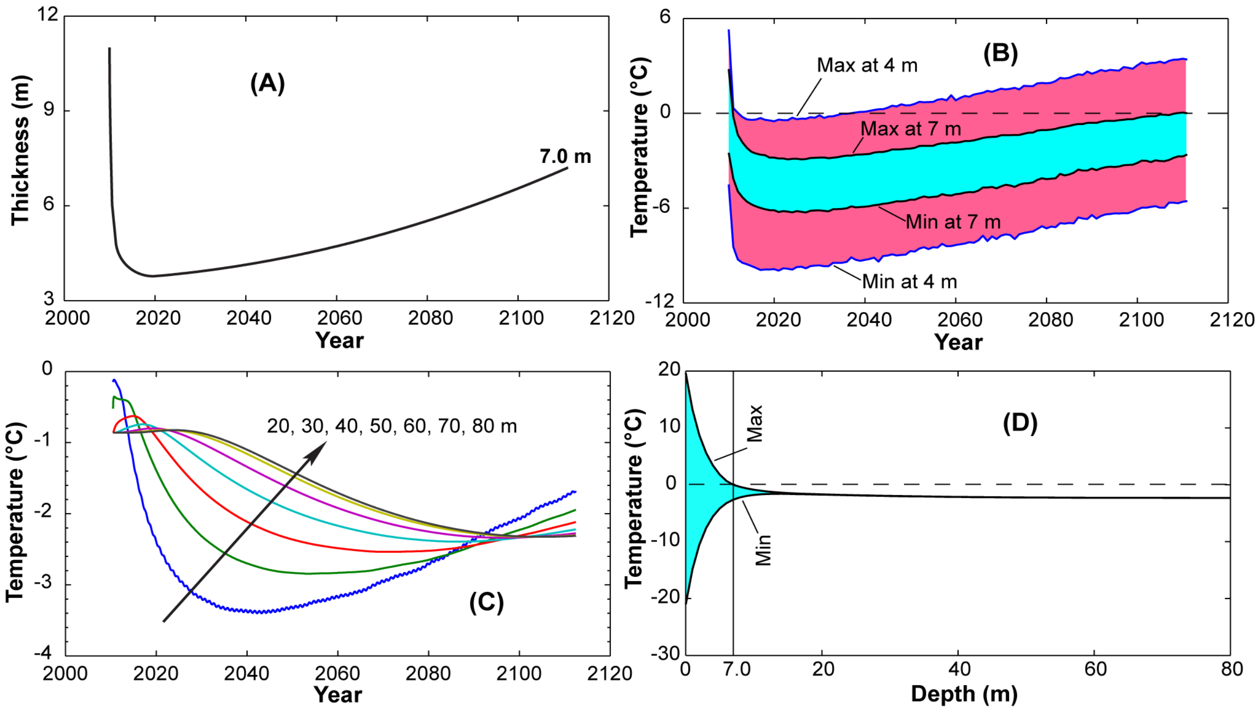

Figure 8.Case 1 scenario simulation results: 0 °C isotherm variation (A), temperature amplitudes at 4 and 7 m (B), temperature variations between 20 and 80 depths (C), minimum and maximum temperatures in the year 2110 (D).

Case 2

In Case 2, where a cover is placed on the Type III waste rock, the 0 °C isotherm rises in the first three years to 3.0 m, which is the top of the till, and remains there until 2040 due to latent heat effects in the till. Then, it gradually rises to a depth of 3.9 m (0.9 m into the till) by 2110 (Figure 9A). Similarly, the maximum temperature at the top of the till rapidly declines to a temperature just below 0 °C and stays constant until 2040. Then it increases slowly to 1.9 °C by 2110 (Figure 9B). The minimum temperature reaches -10.1 °C in the year 2020 and increases to -5.1 °C in the year 2110 (Figure 9B). At the base of the till, the temperatures remain colder than 0 °C. However, the maximum temperature ranges from -1.1 to -0.3 °C between 2020 and 2110 respectively. The minimum temperature is colder, varying from -9.2 to -3.6 °C between 2020 and 2110 (Figure 9B).

Temperatures below 20 m depth show similar results as discussed in case 1 but with significantly smaller deviations due to latent heat stored in the till (Figure 8C and Figure 9C). Figure 9D shows the 0 °C isotherm penetrates 0.9 m into the till (or 3.9 m from the surface) by 2110 and the figure also shows the depth of zero annual amplitude is at about 20 m.

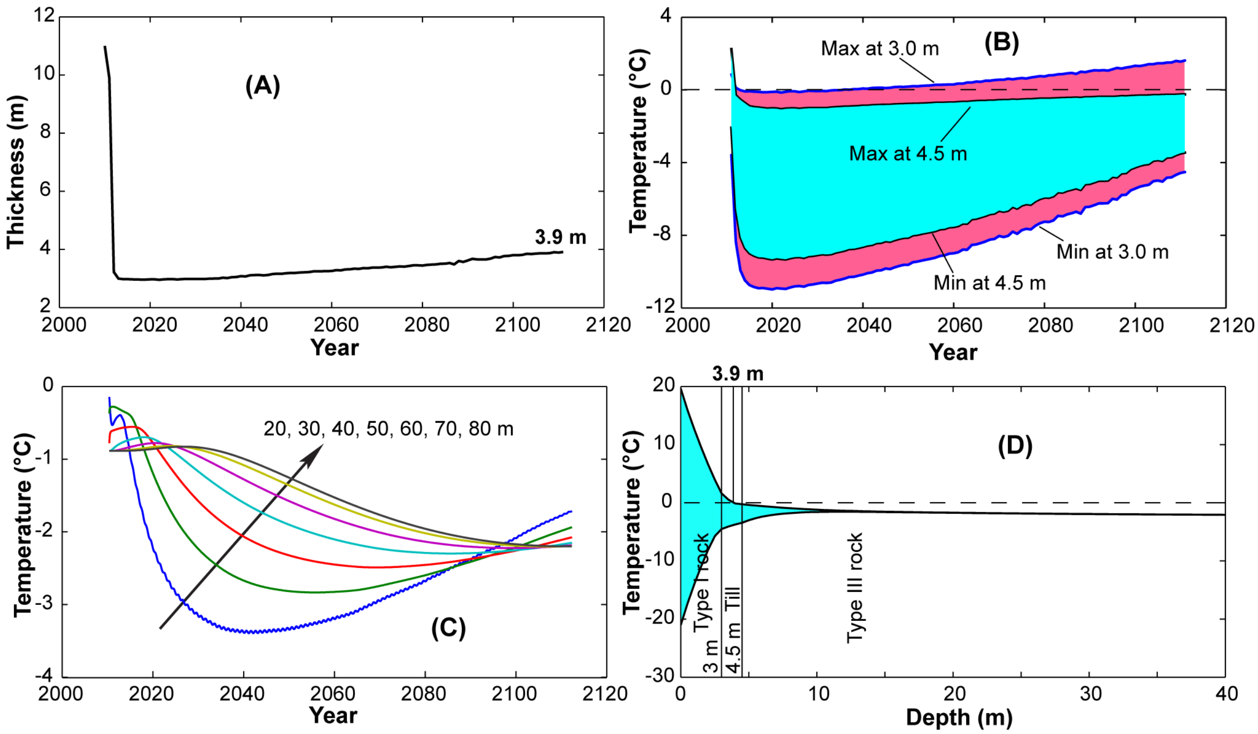

Figure 9. Case 2 scenario simulation results: 0 °C isotherm variation (A), temperature amplitudes at 3.0 m (top of the till) and 4.5 m (bottom of the till) (B), temperature variations between 20 and 80 depths (C), minimum and maximum temperatures in 2110 (D).

Conclusions

Measured air temperatures over the 10-year period (2000 - 2010) at the Diavik site has a MAAT of -9.1 °C and trend lines indicate warming of the air temperature expressed through the changes of freezing, thawing indices and numbers of freezing and thawing days. Based on air temperatures measured at the site, and other long-term air temperatures recorded at nearby locations, future climate modeling predicts the highest and lowest rates of temperature change occur in January and July respectively; while predictions for October and April indicate slight mean annual increases.

Ground temperature measurements in the Type I waste dump indicate the 0 °C isotherm is currently at 11 m below the surface and conductive heat transfer in the pile controls the temperature variations. No observations of increased temperatures due to oxidation of sulphide minerals have been recorded and the calculated thermal diffusivity from ground temperatures is comparable to measured values found in the test piles at the Diavik site. 1D conduction numerical modeling (case 1 without a cover) predicts the 0 °C isotherm will be at 7 m with climate change by 2110. In case 2, with the aid of a saturated till layer, the 0 °C isotherm rises to 3.9 m below ground surface. Ground temperatures below 20 m of case 1 and case 2 are similar.

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