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1-Introduction

In 2009, the Yukon Government implemented a light-colored asphalt pavement on Front Street, Dawson City, YT. The objective of the project was to mitigate the thermal effects of pavement, through the albedo effect, on potentially ice-rich permafrost underlying the street.

At this occasion, boreholes were drilled, and thermal sensors were installed beneath the street with DC electrical resistivity arrays. The objective was to monitor the performance of the pavement.

Following the 2009 re-surfacing, no significant data analysis was carried. The objective of the present survey is to analyze Dawson's Front Street Performance (since re-surfacing) based on the ground thermal data collected and provided by Yukon Government. Based on the result of the analysis, some recommendations for potential follow-up work are provided.

1.1 Summary of the Front Street project timeline

The boreholes were drilled in June 2009. Nine boreholes were performed by the Kryotek Company down to a depth of 6 meters. From these 9 boreholes, 4 were selected for instrumentation, and BeadedStream loggers were installed only few days after the drilling. For convenience, each station is named from its location for this report (Figure 1.1). From the South to the North, the four stations were installed at:

1- GRAY: in front of the Holland America Tours store, AKA Gray Line Yukon;
2- IVORY: in front of the Klondike Nugget and Ivory Shop;
3- GOLD: in front of the vacant lot of the Gold City Tours office;
4- BERM: on the berm side, in front of the parking lot between Duke and York streets.

Paving happened in two stages. The first lift of asphalt was the standard black product. This occurred after the instrument installation, the last week of August 2009 under a hot and sunny weather; It is assumed that lots of heat were transferred into the ground. This was followed by the placement of the pigmented asphalt (bituclar) from September 12 to 15 2009.

As Discussed in the section 4, two loggers failed or were vandalized relatively early (July 2009, and November 2009), whereas the two others stopped to work in November 2010 and July 2011.

Consequently, a second round of installation/repairs occurred on May 2 2012 with loaned loggers, while the original loggers were sent to the manufacturer for repairs.
2012 (Date?). We had issues with the original loggers. The loaned logger were then replaced with the current loggers on October 8 2012.

Consequently, major gaps are present in the data set. As discussed in Section 4, due to additional malfunctions of the loggers, some additional concerns appeared after the careful inspection of the data set.

1.2 Analytic approach

To have a better understanding of the permafrost thermal regime under Front Street, it is important to consider: 1- the geological properties of the sites; and 2- the climate trend of the past and recent years since the implementation of the pavement.

Both geological and climate aspects are studied in Section 2 and 3 respectively. The knowledge about the nature of the ground helps to understand specific difference among each site/borehole, whereas understandings about climate trends may help to discriminate the thermal influence from the weather from the one of the pavement, and to understand the potential changes to permafrost temperature regimes along Front Street in the recent past years.

Finally the analysis of permafrost temperature profile by comparison with geocryologic logs for each site may allow to identify potential future permafrost conditions and thaw sensitivity along Front Street.

The analysis of the permafrost temperature regime focuses, when possible, on permafrost temperature, yearly and seasonal ground temperature fluctuation, evolution of the active layer thickness (thaw depth) for each sites, with an crossed comparison between each borehole to understand site specific factors.

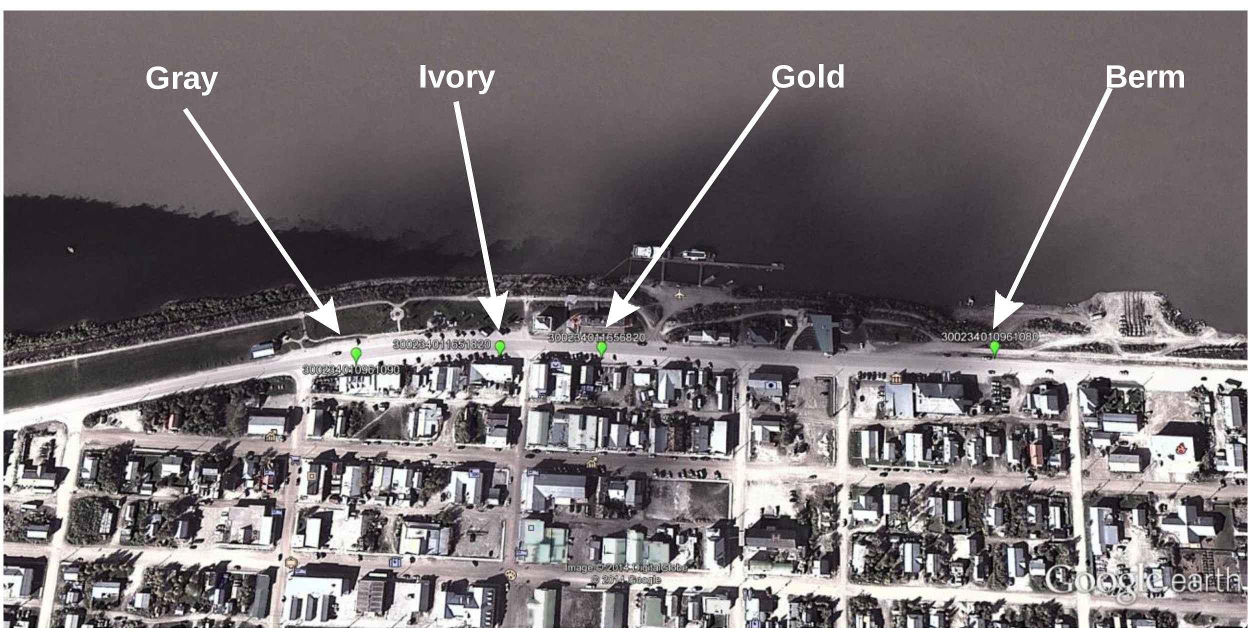


Figure 1.1. Location of the logging stations

2. Geological setting at Front Street

2.1. Dawson General permafrost setting

The town of Dawson is located in a valley at the confluence of the Klondike and Yukon Rivers, at the northern limit of the discontinuous permafrost zone. Brown (1970) reported that the permafrost is about 60 m deep, and could be found close to the ground surface in most sections of town except for the south where the Klondike River has deposited sand for a distance of about 180 m from its present bank. The condition of older buildings testifies of the thawing of the underlying permafrost and the extensive frost action in the active layer.

The entire town site is situated on a thick permanently frozen gravel pad of undetermined thickness over which lies a 2 to 6 m thick layer of fine grained, organic rich at some location, soil. This gravel was deposited during the last deglaciation, when the valley was formerly occupied by the fast flowing Yukon River. This gravel is shown in red in the cross-sections of figure 2.1 that shows the nature of the deposits underlying Dawson. The gravel was deposited directly over the bedrock surface. This surface being uneven and pitted with depression, it results that the gravel layer varies in thickness depending on the topography of the bedrock (EBA 1977).

Later on, as the flow of the Yukon River decreased, finer sediment were deposited, consisting of silt forming a terrace above the coarse deposit (shown in yellow in the cross-sections of figure 2.1). Concurrently, the delta of the Klondike River advanced, laying down silty sand over bedrock and gravel at the south side of the city site (shown in orange in the cross-sections of figure 2.1). A gully locally known as the “slough” roughly delineates the limits of the deltaic deposits.

Finally, filling material has been laid down on the original ground surface at numerous locations. This material can consist in any kind of matter that can be laid down by man, ranking from gravel to trash.

Permafrost is present in the coarse glacio-fluvial deposit and in the fluvial silt deposit overlaying the gravel, whereas it is absent in the deltaic silty sand. This is due to the fact that the silty sand is denser and has a lower latent heat than the silts. Consequently, permafrost is widespread throughout the townsite, but it is not continuous. The slough roughly delineates a line dividing the southern and northern part of town in term of permafrost distribution. In the northern part of town the overlying soil is predominantly high ice content silt and peat containing frequent ice lenses, while in the southern part of town, the soil is predominantly non-frost-susceptible sand where unfrozen soil was encountered at depth in all boreholes drilled south of Church Street (Baldwin and Heinke 1973).

While gravel deposits appears to be relatively ice poor (less than 10%), the silt deposit shows higher excess ice content because of its higher water content and its fine grained nature favoring the formation of segregated ice. This ground ice occurs in the form of lenses and layers intermingled with the sediment. Excess Ice content ranging from 10 to 25% of the total soil volume frequently has been reported in geotechnical log. EBA estimated that subsidence up to 0.5 m could occur if the accumulated thickness of excess ice above the "gravel" were allowed to melt. Spatially, the excess ice content ranges from nil close to the Slough area to a maximum near the valley wall to north east.

In the permafrost area, the active layer was estimated at about 2 m in roads and about 1.7 m in areas having an organic cover, while in the non-permafrost area, the seasonal frost penetration varies from 2.0 to 2.7 m with an extreme of 4 m having been reported.

Due to the poor drainage conditions in the area, the permafrost level is gradually receding. Artesian springs have been reporter such as near the S.W. corner of Sixth and King, where an artesian groundwater source was encountered at a depth of 1.8 m (E. W. Brooker and Associates, 1972).

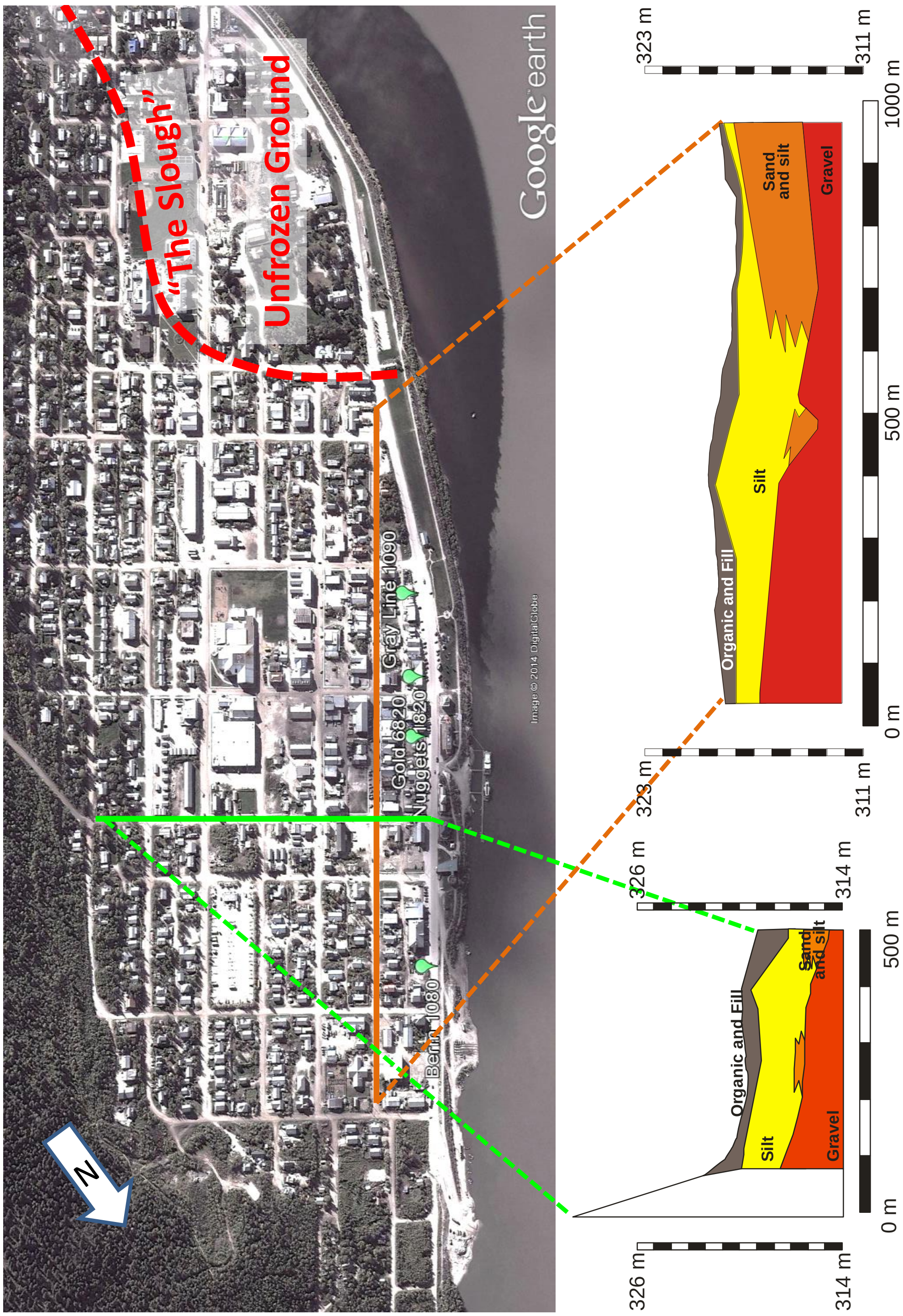


Figure 2.1. Stratigraphy of Dawson City

2.2. Front Street permafrost setting

The NS cross section presented in Figure 2.1 is a synthesis of borehole logs performed by EBA (1977). It is the closest representation of the ground profile along Front Street. All the deposits that were discussed in section 2.1 are present (Gravel, silt and deltaic sand). It has to be noted that the thickness of organic and fill increase from East to West in the EW cross section. Indeed it has been reported that Front Street has been raised about 3 m above natural ground level to act as a levee against flooding from the Yukon River. Some EBA reports indicate that the filling consisted of coarse tailings.

This detail is important as it emphasizes the fact that Front Street is possibly one of the most altered and disturbed street of Dawson City. Figure 2.2 shows the state of the street circa 1898, during the Gold Rush era.

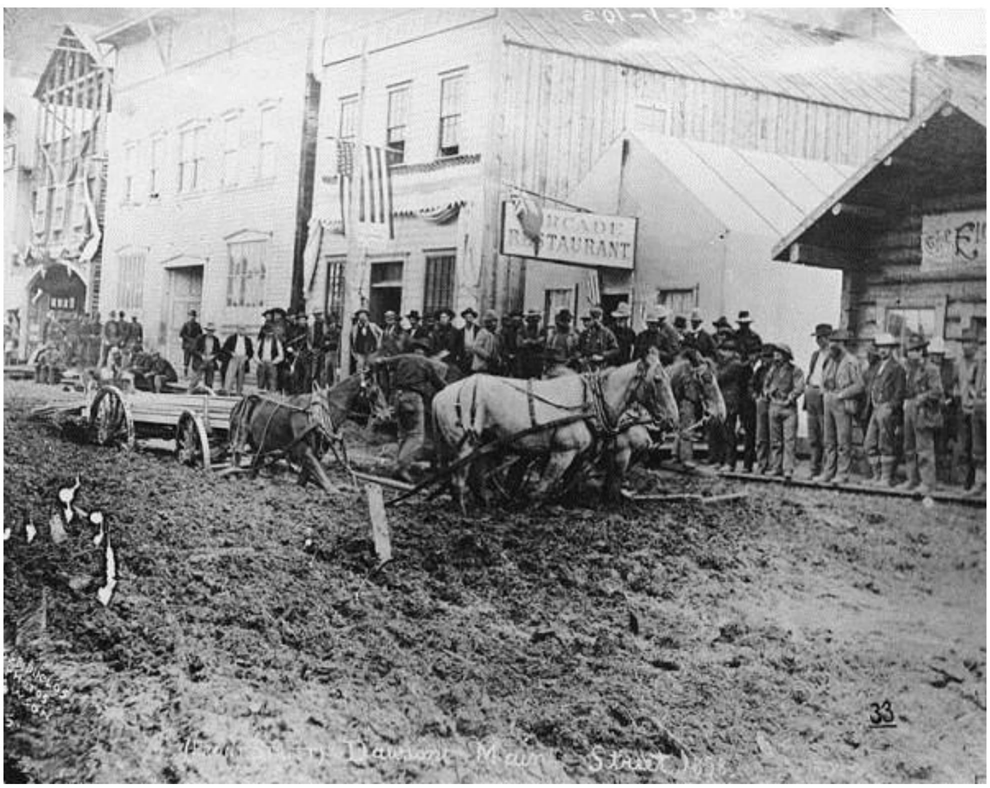


Figure 2.2. Front Street, Dawson Citt, Circa 1998.

Later on, The surface of Front Street still underwent various alteration such as reported by Baldwin and Heinke (1973) that described the surface of the street as “so heavily oiled that it resembles asphalt”(figure 2.3).

Figure 2.3. Closeup of Front Street road surface
"So heavily oiled that it resembles asphalt", May 25, 1972 (Baldwin and Heinke, 1973).

Due to its history, the first meter of the ground profile below Front Street have been deeply altered form its original condition. Figure 2.4 shows the logs of the boreholes drilled by Kryotek along Front Street by in May 2009. The logs are consistent with observations. From the top to the bottom, the first meters of the ground profile consistently consist of coarse grained, heterogeneous material. The first unit, shown in grey in the logs of figure 2.4, is fill material. The second unit, shown in red, appears to be more gravelly and is likely fill material also. The third unit, in yellow in the logs of figure 2.4, is silty to sandy sediment and is more likely to be original ground. At some location (Bh2 and Bh7), another gravel unit is observed below the silt that is consistent with the geologic setting of town site.

At the time of the drilling, no permafrost was observed in the boreholes located at south of the city, as it could be expected. The permafrost top was observed between 2.5 and 5 m depth at the other sites.

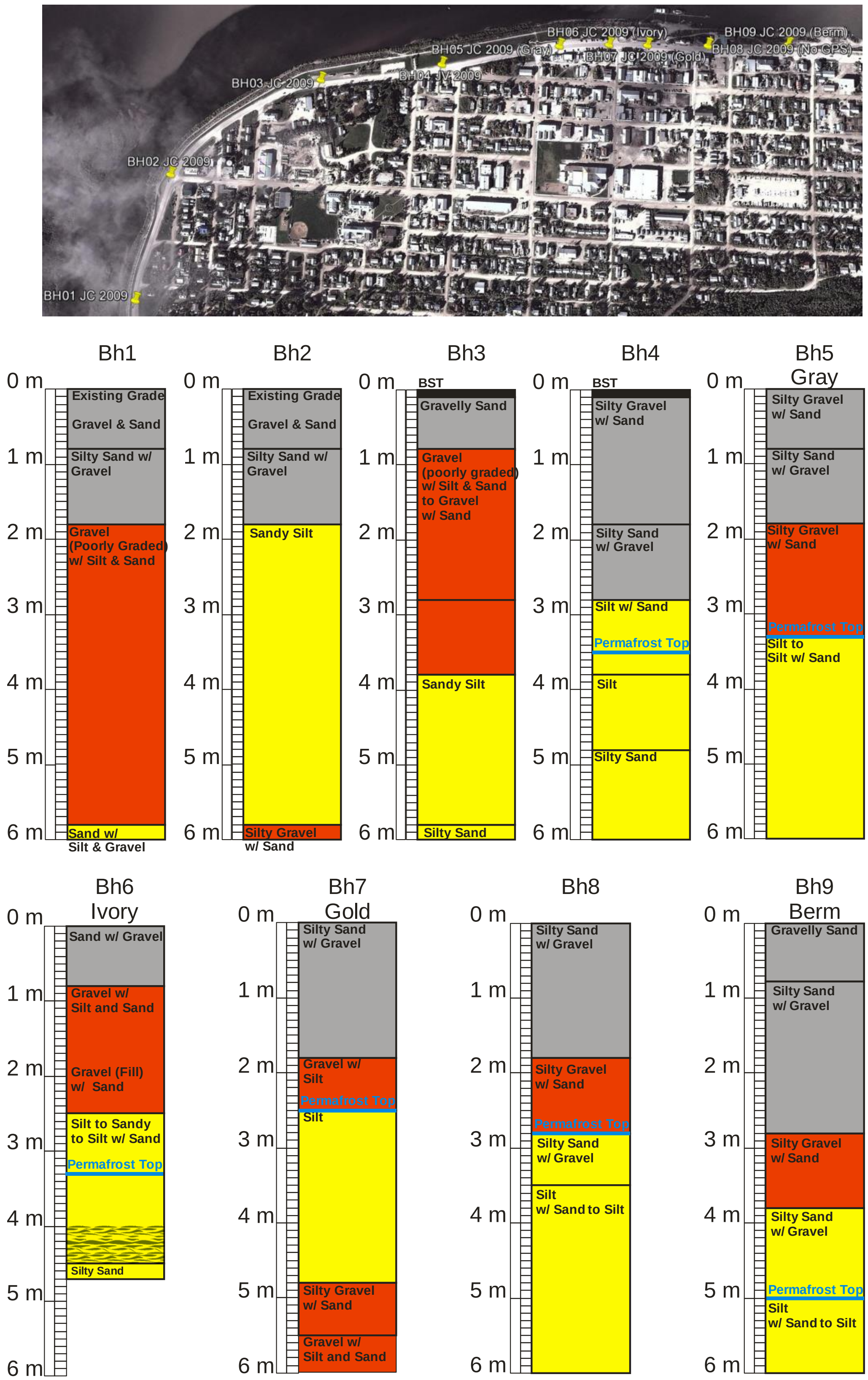


Figure 2.4. Boreholes logs from Front Street performed by Kryotek in May 2009

Significant amount of excess ice, between 20 and 30%, were reported in Bh6, from about 4 to 4.5 m depth. No more to 1% of excess ice was reported at the other location except for Bh8 with 10% at about 5.5 m.

Four boreholes, Bh 5 (Gray), Bh 6 (Ivory), Bh 7 (Gold), and Bh 9 (Berm), were instrumented with BeadedStream loggers allowing to record 10 ground temperature at 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, and 5 meters (Figure 2.5).

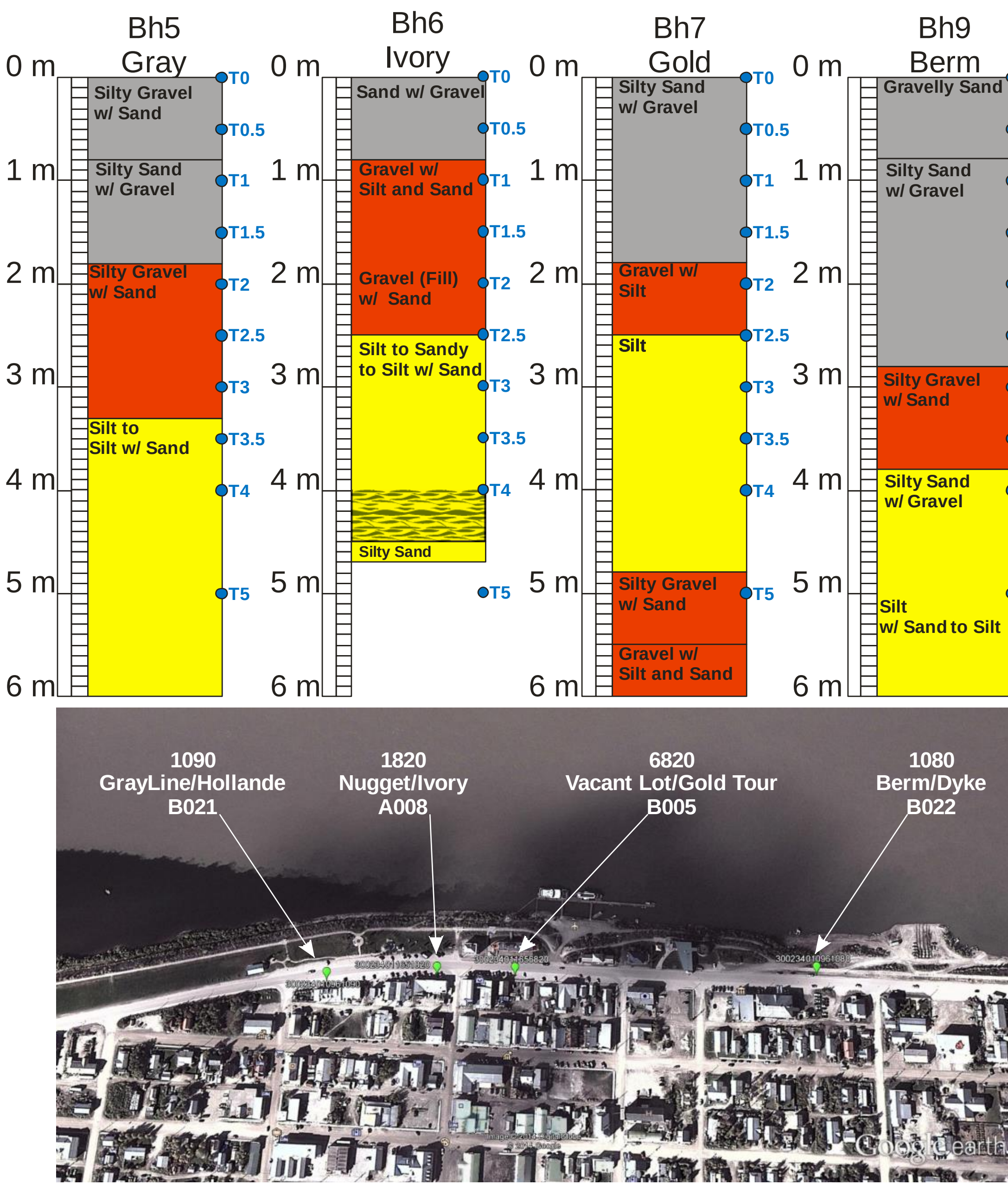


Figure 2.5. Logs and locations of the instrumented boreholes along Front Street

3. Climate records in Dawson City area

3.1. Climate record from 1900 to 2010.

The data used in this section were provided by Environment Canada. Data from three stations were combined to provide a dataset of over 100 years. These stations are: Dawson, 2100400; Dawson A, 2100402; and, Dawson, 2100LRP. The latter is the automatic station at the Dawson airport. These stations had periods of overlapping observations, so direct comparisons could be made between them. The stations 2100400 and 2100LRP had their observations adjusted to correspond to those of 2100402.

Michael Purves, Meteorologist Ret'd at the Yukon Weather Centre, performed the data analyses that are provided here as a personal communication.

The precipitation and temperature data were obtained from the monthly records: Summer was defined as being May 1 to August 31; Winter was defined as being November 1 to the last day in February. The year of the winter considered was taken to be that for November. Changes in temperature are given in degrees Celsius per Century (d/c). Changes in precipitation are given in percent per century or in millimetres per century (mm/c). The change in percent is calculated using the regression coefficients calculated by Excel. Given the regression equation:

Pcp Amt = A + B*Years

The change per century is simply:

B*100 mm

And the percentage change is:

B/A*100%

3.1.1. Mean Daily Minimum in winter

The data show two major periods of warming (figures 3.1). The first, from1902 to 1925, had an increase of 10.9 d/c. The second and more significant, from 1964 to 2005, had an increase of 18.0 d/c. There was a period of cooling from 1940 to 1964 with a decrease of 14.5 d/c. Over the period of record, Dawson shows an overall increase of 2.6 d/c. The change over the last 30 years, 6.2 d/c, is very significant and has been noted by many people in terms of their own life experience that winters are not as cold as they used to be.

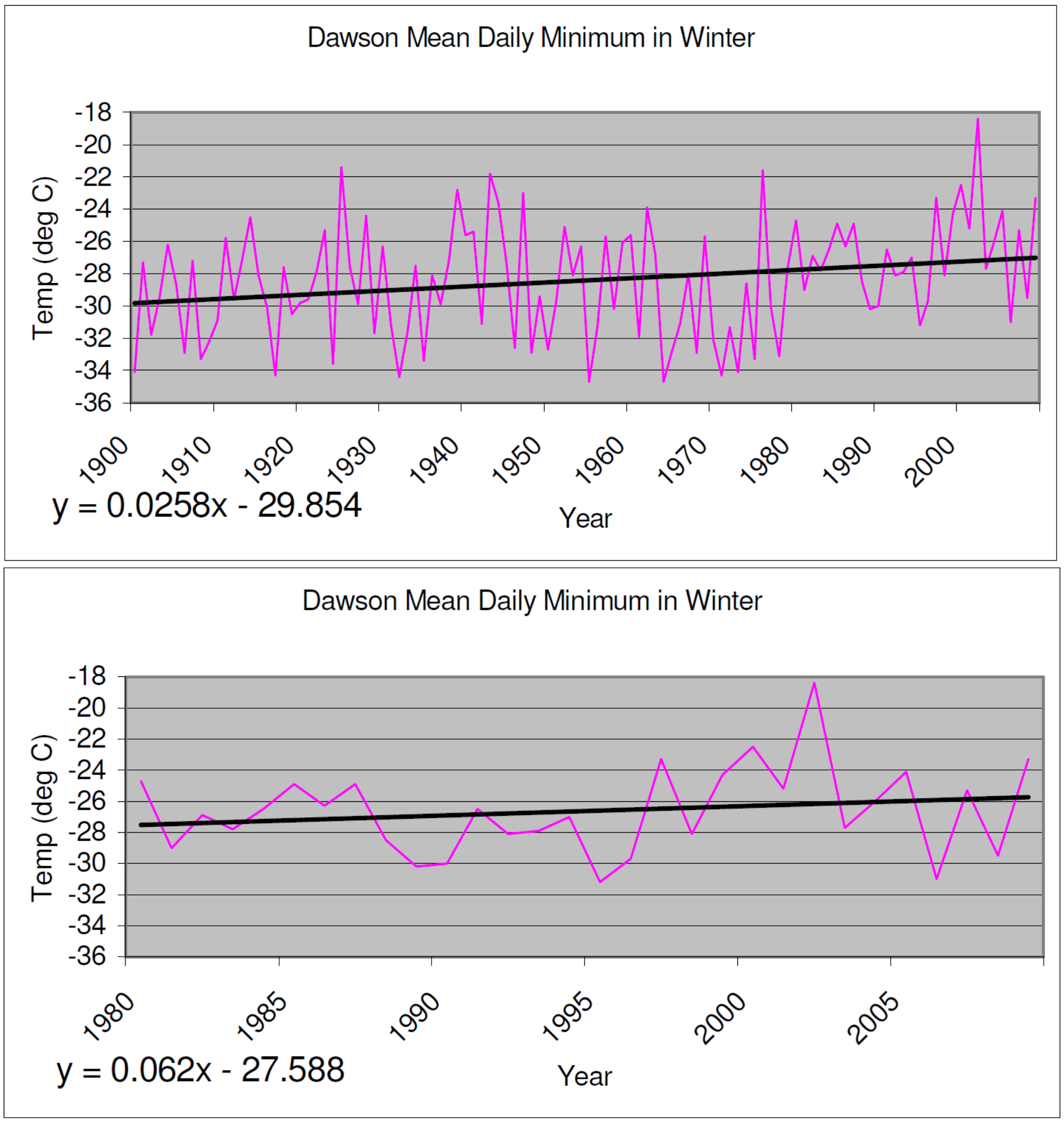


Figure 3.1. Dawson Mean Daily Minimum in Winter for 1900-2009 and 1980-2009 periods.

3.1.2. Mean Daily Maximum Temperatures in Summer.

The data record covers all but three summers (1913, 1927 and 1933) from 1901 to 2010 inclusive. As with the winter temperatures, the summer temperatures show two periods of significant warming and one of cooling (figure 3.2). The first period of summer warming was from 1901 to 1923 with an increase of 4.0 d/c. Over the past thirty years, there has been an increase of 3.8 d/c. There was a period of cooling from 1941 to 1964 of 7.8 d/c. Over the entire period, the rate of warming of the mean summer daily temperature is 0.9 d/c.

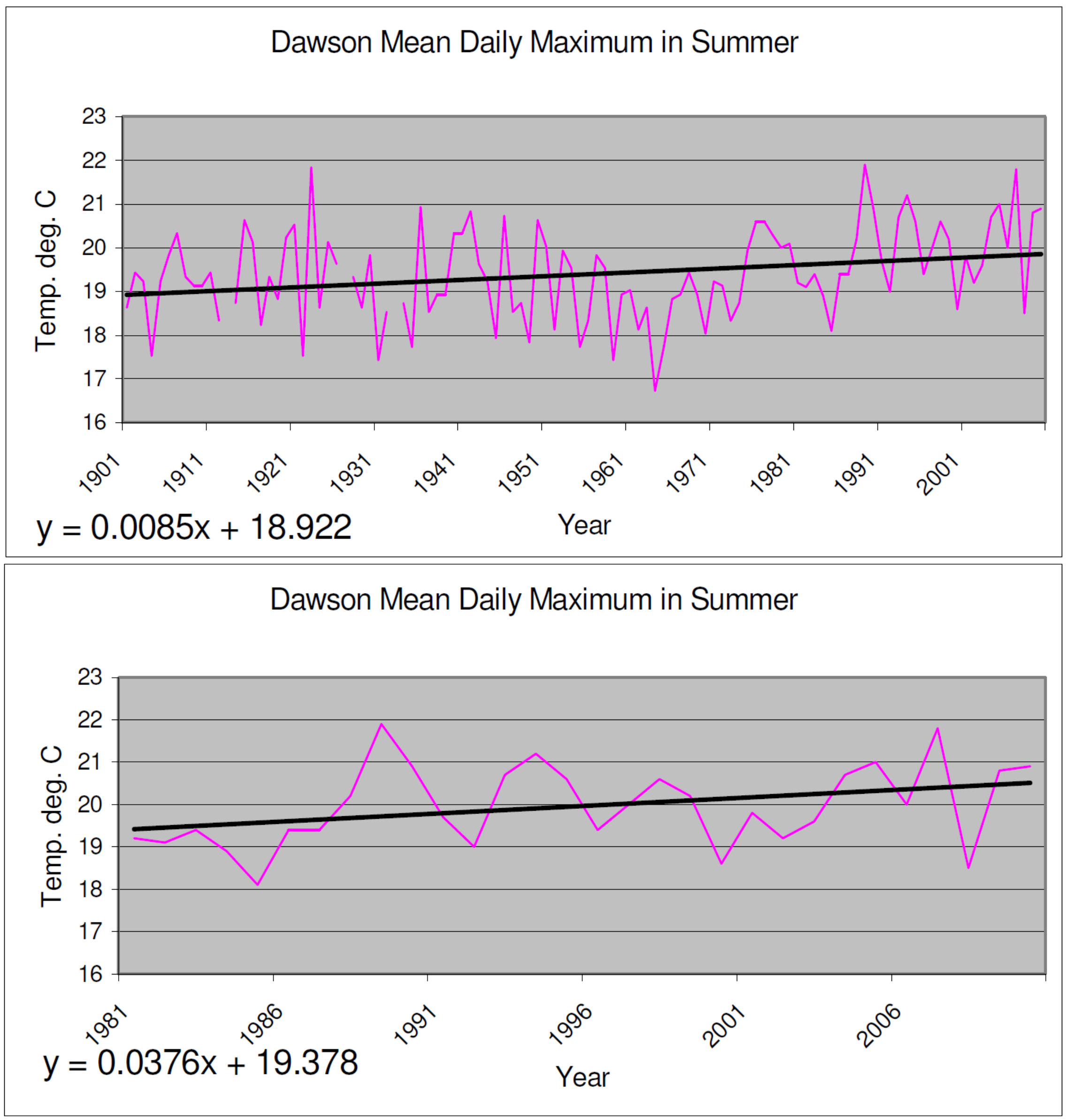
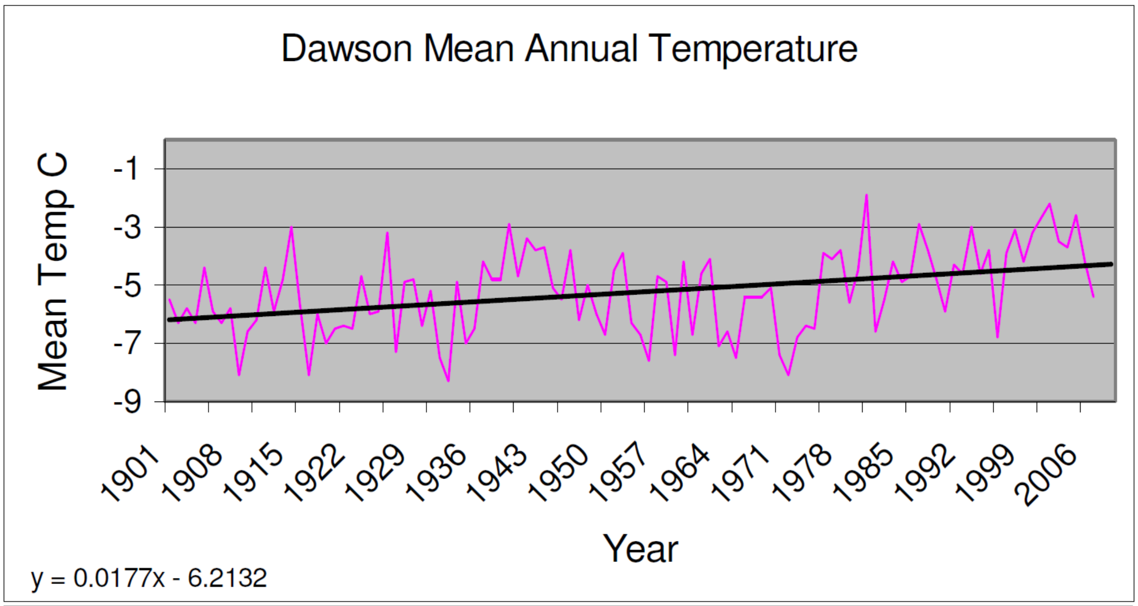


Figure 3.2. Dawson Mean Daily Maximum in Summer for 1900-2010 and 1981-2010 periods.

3.1.3. Mean Annual Temperature.

As with the winter temperatures, the annual temperatures show two periods of significant warming and one of cooling (Figure 3.3). The first period of warming was from 1915 to 1943. There was cooling from 1943 to about 1978 with more warming since that time. Over the past thirty years, there has been an increase of 2.4 d/c. Over the entire period, the rate of warming of the mean annual temperature is 1.8 d/c.



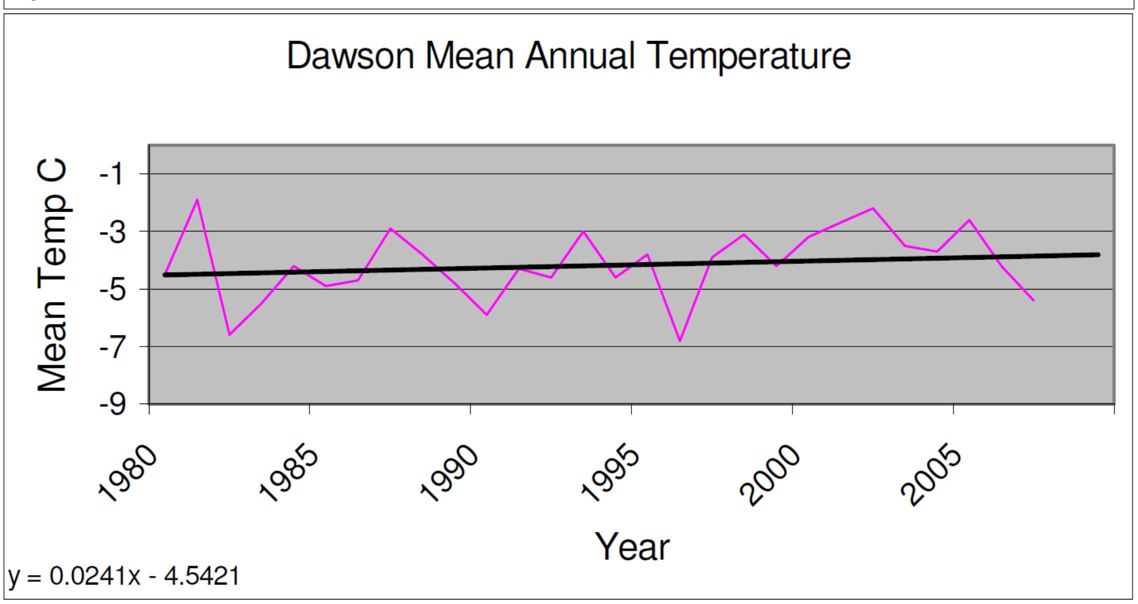
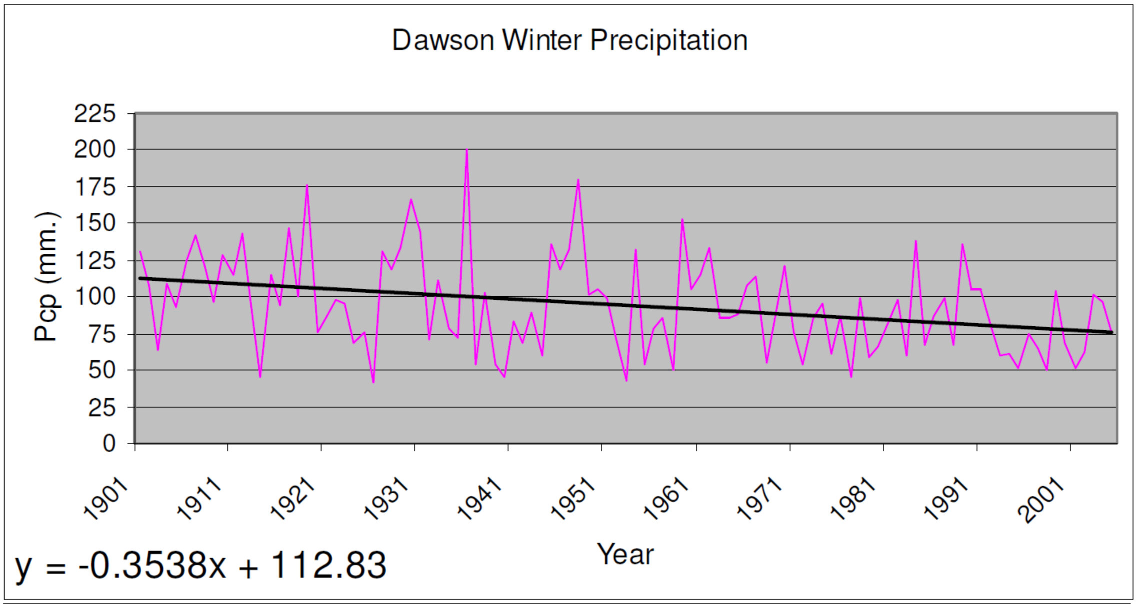


Figure 3.3. Dawson Mean Annual Temperature for 1901-2009 and 1980-2009.

3.1.4. Total Winter Precipitation.

While there are some signs of wetter and drier periods over the length of the record, the record generally shows decreasing amounts of precipitation amounting to a decrease of 35.4 mm/c, a rate of 31% over the last century (Figures 3.4). Over the past thirty years of record (1976-2005), the precipitation is down 22.6 mm/c, or about 27%.



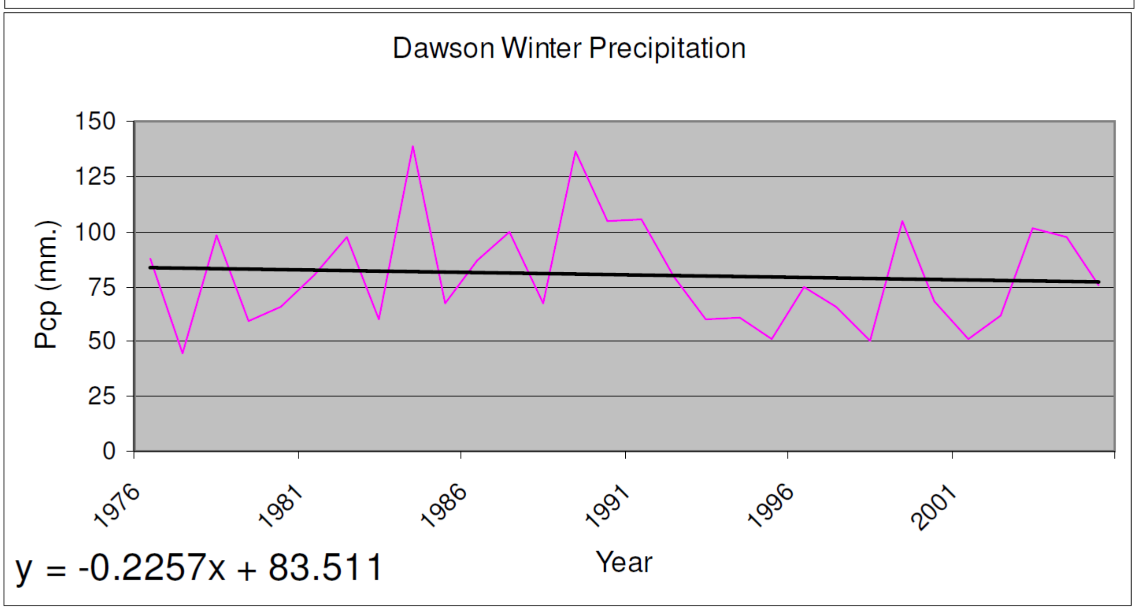
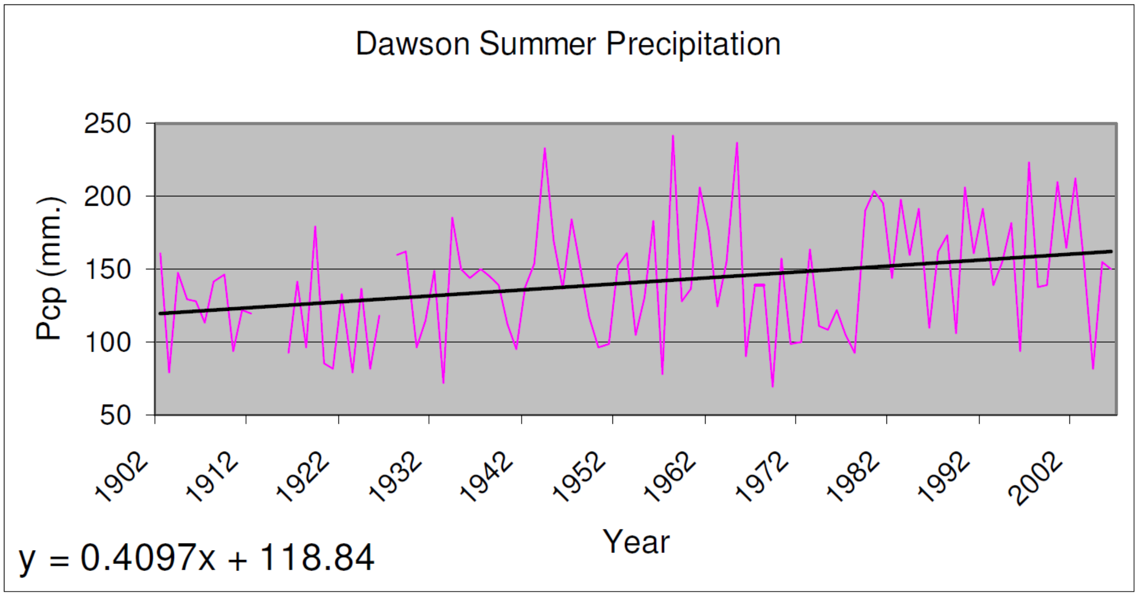


Figure 3.4. Dawson Winter Precipitation for 1905-2005 and 1976-2005 periods.

3.1.5. Total Summer Precipitation.

The first thirty years of record seem drier than the remainder (Figure 3.5). Overall, summer precipitation seems to be up about 34%/c (41 mm/c). Over the past thirty years, summer precipitation seems unchanged, being down just 3 mm/c or 2%.



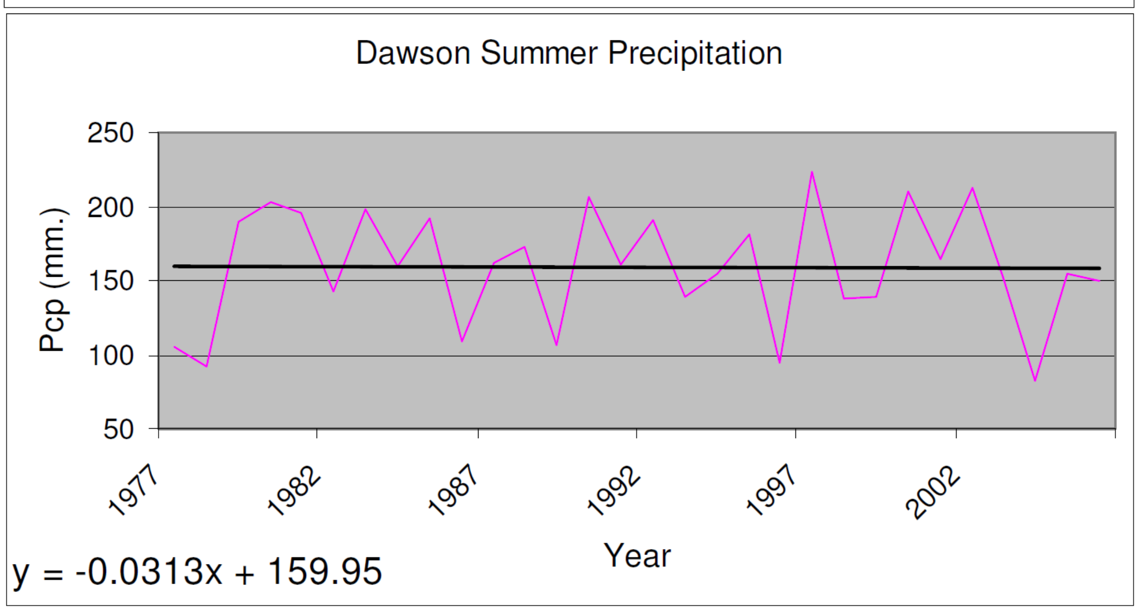
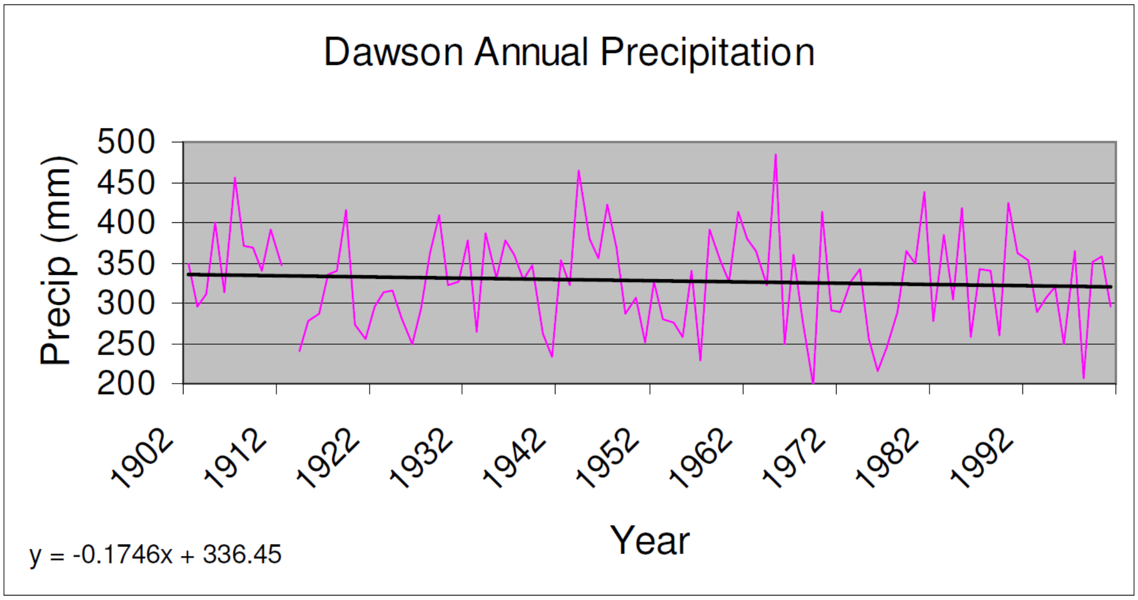


Figure 3.5. Dawson Summer Precipitation for 1902-2006 and 1977-2006 periods.

3.1.6. Total Annual Precipitation.

The data show wide fluctuations from year to year, but a slight decrease is noted overall of about 5 %/c, or about 17 mm/c (Figure 3.6). Over the last thirty years of record, precipitation is up slightly by 45 mm/c or 14%.



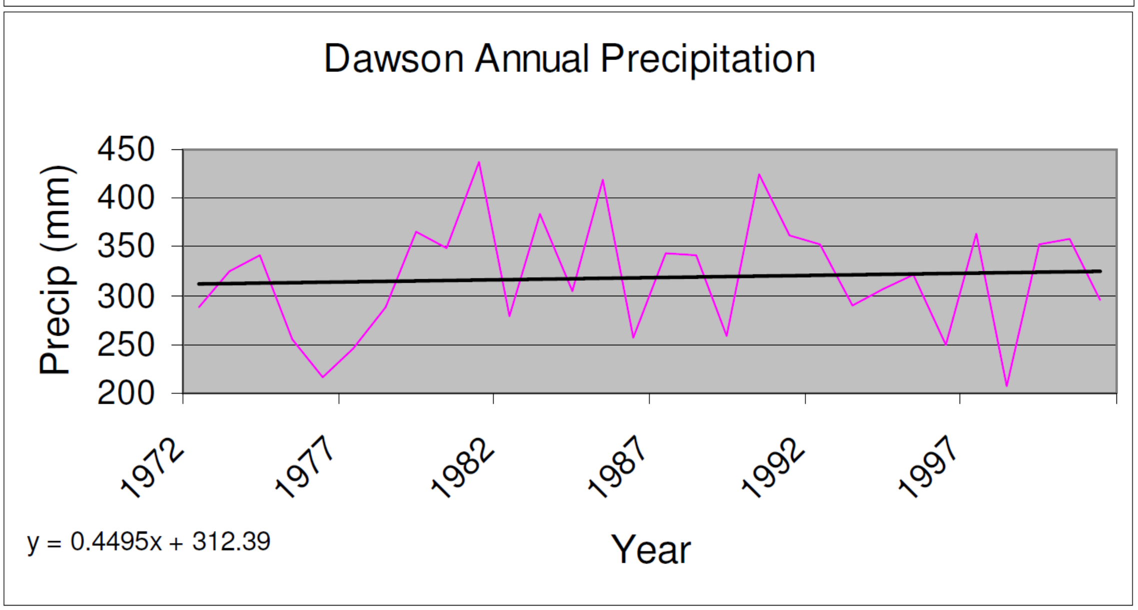


Figure 3.6. Dawson Annual Precipitation for 1942-2010 and 1981-2010 periods.

3.1.7. Snow on Ground for February 28

Snow on Ground Data for the years 1955 to 2010 show a strong decrease over the years, amounting to 65 %/c or 47 cm/c (figure 3.7). Over the past thirty years, the snow depth on the last day of February is down at a rate of 28 cm/c or 50%. Station 2100400 was used until 1975 and station 2100402 for the following years, except station 2100LRP was used for the reading for 2008 and 2010 with no observations for the year 2009. It is impossible to say what effect the change in station location has had on the snow depth data.

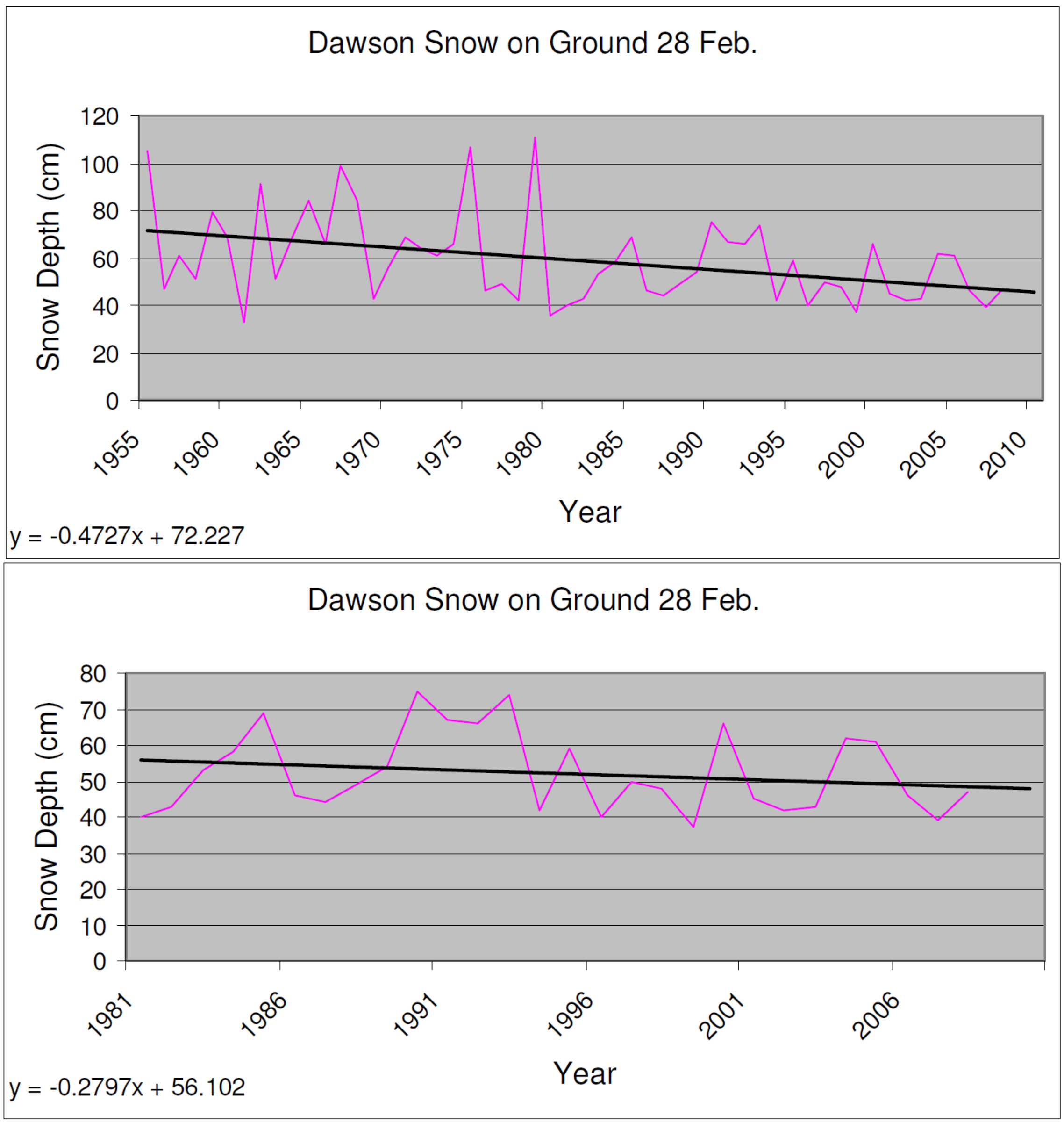


Figure 3.7. Dawson Snow on Ground for 1955-2010 and 1981-2010 periods.

3.1.8. Days Below –40 C.

Although the data from Dawson do show some long-term cycles in the number of days with temperatures below –40C, over the full period of record there is no apparent trend (figure 3.8). On the other hand, over the past thirty years, the number of days below with temperatures below –40 have decreased at a rate of 39 Days/c or 168%. If this trend continued, there would be no days below –40 by the year 2040.

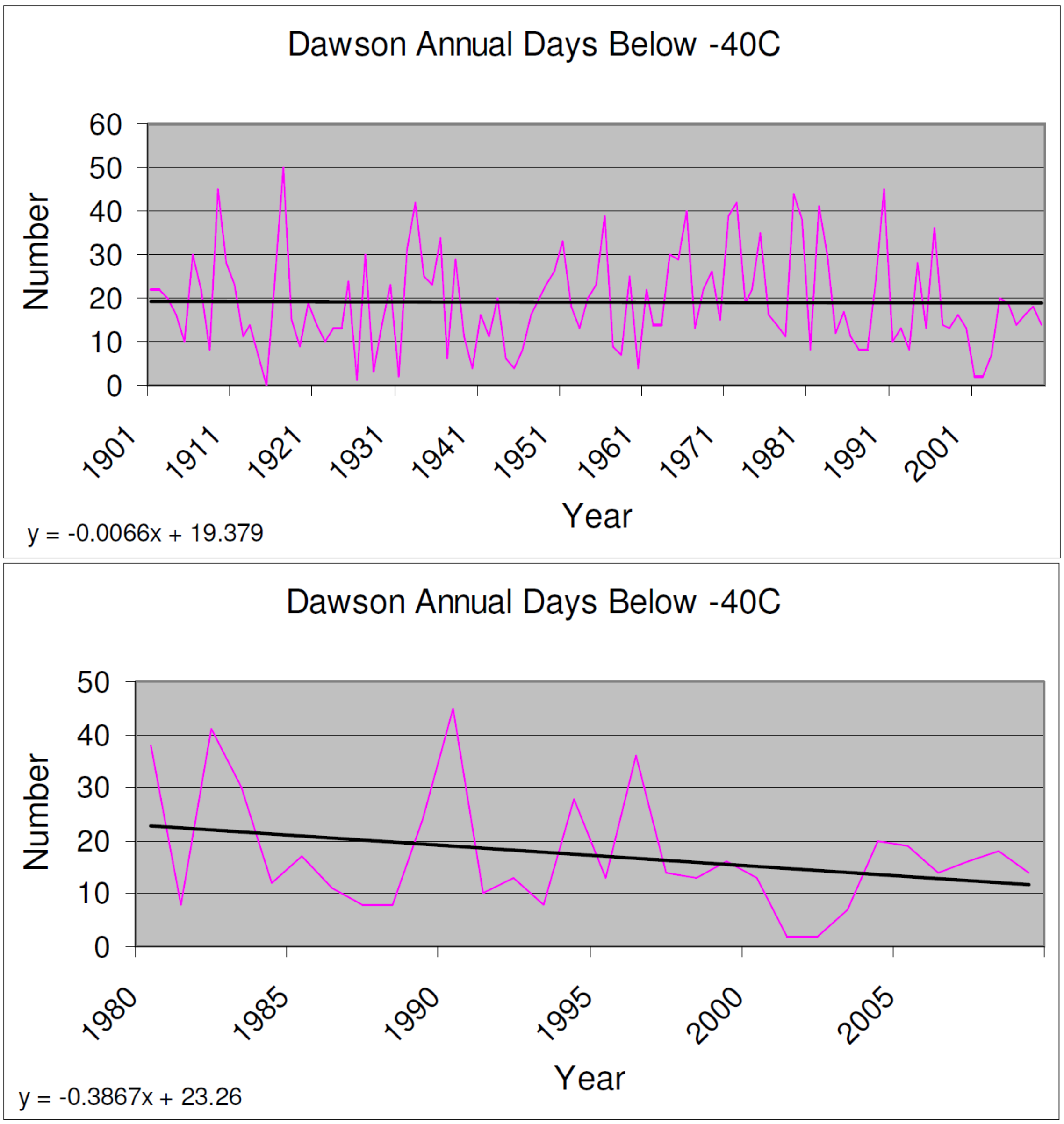


Figure 3.8. Dawson Annual Days Below –40C for 1901-2009 and 1980-2009 periods.

3.9. Frost-Free Days.

The data for Dawson, from 1901 to the present, show some long-term cycles in the number of frost-free days, but over the full period of record there is an increase of 32 days/century or 75% (figure 3.9). Over the past thirty years, the number of frost-free days increased at a rate of 74 days/century or 118%. The data was obtained from three different stations, and they were adjusted to match, as well as possible, data from similar periods from station 2100402.

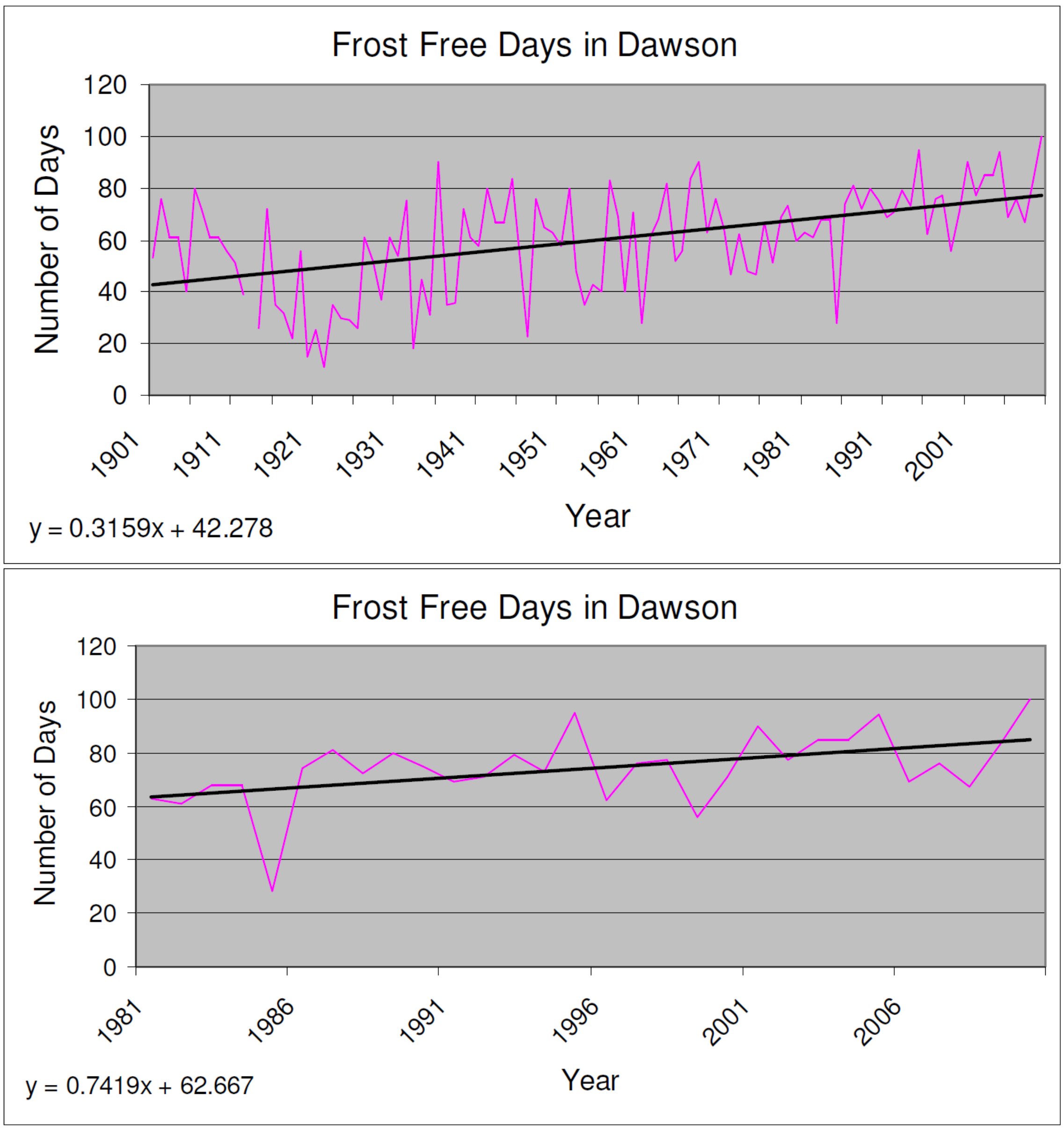


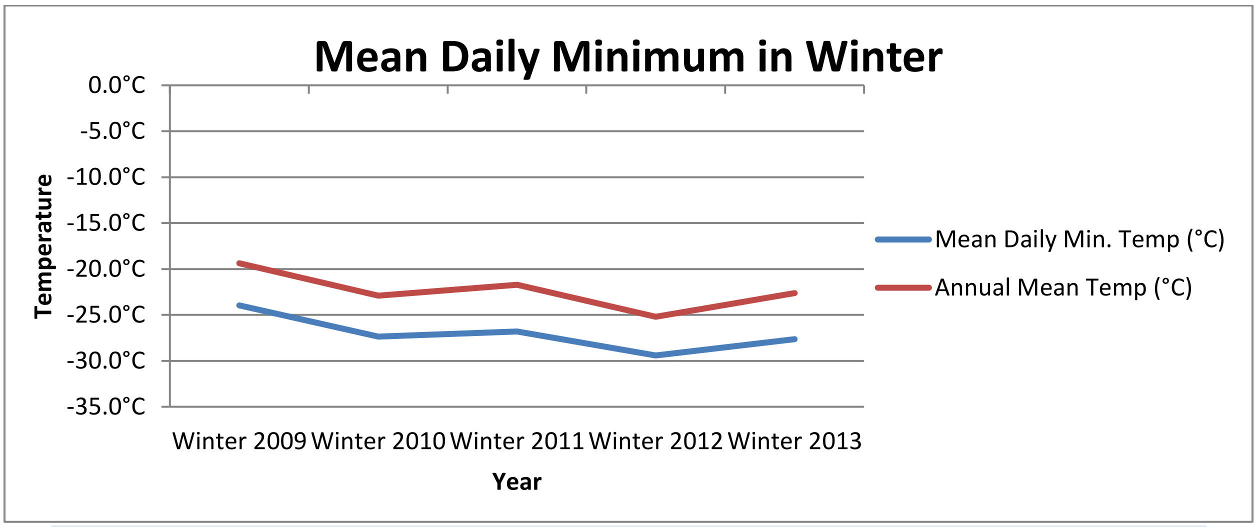
Figure 3.9. Dawson Frost Free Days 1901-2010 and 1981-2010 periods.

3.2 Climate records from 2009-2013

The data used in this section were provided by Environment Canada, and are from the automatic station at the Dawson airport (2100LRP). The dataset covers the period of implementation of the new pavement from 2009 to 2013. The 2014 winter also has been considered as the data were available at the time of this survey.

3.2.1. Mean Daily Minimum in Winter

The data show that Mean daily minimum temperatures in winter range from -24 to -29.4°C for the 2009-2014 period (figures 3.10). The coldest mean daily minimums were observed in 2012 and 2013; Temperatures appearing to get colder from the beginning to the end of the period. Extreme minimum temperature can be expected to have an impact on the shallowest ground temperature, but not influence the deepest one.

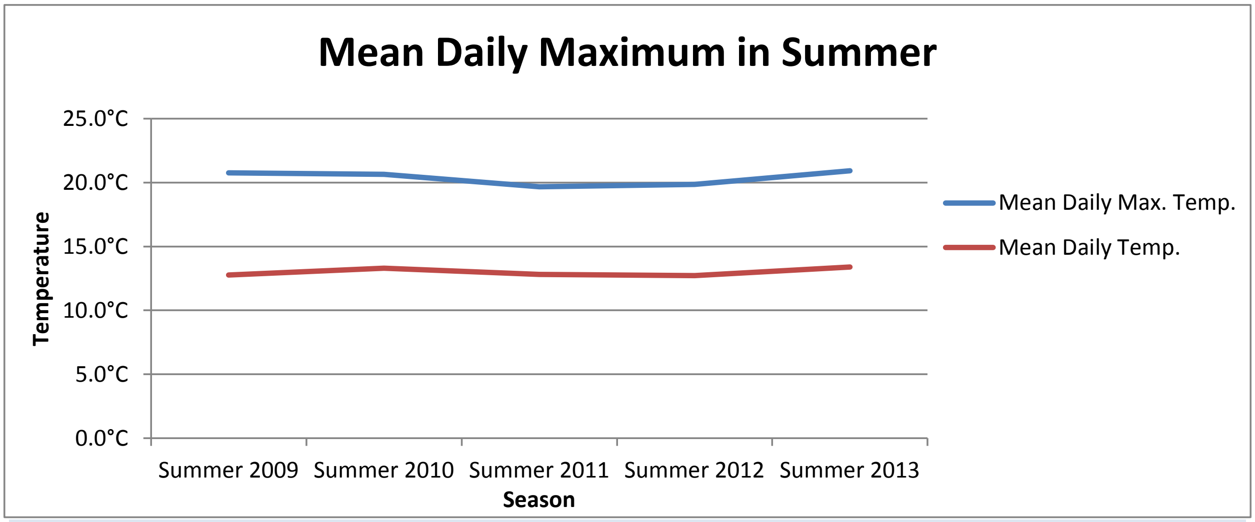


	Main Daily Minimum Temperature	Mean Daily Temperature
Winter 2009	-24.0°C	-19.4°C
Winter 2010	-27.4°C	-22.9°C
Winter 2011	-26.8°C	-21.7°C
Winter 2012	-29.4°C	-25.2°C
Winter 2013	-27.6°C	-22.6°C

Figure 3.10. Dawson Mean Daily Minimum in Winter for 2009-2014 period.

3.2.2. Mean Daily Maximum Temperatures in Summer

The data show that Mean daily maximum temperatures in summer are relatively stable, ranging from 19.7 to 20.9°C for the 2009-2014 period (figures 3.11). The coldest mean daily maximums were observed in 2011 and 2012. Extreme maximum temperature can be expected to have an impact on the shallowest ground temperature, but not influence the deepest one. As these temperatures seem constant from 2009 to 2013, they should not have an influence on the ground temperature profiles.

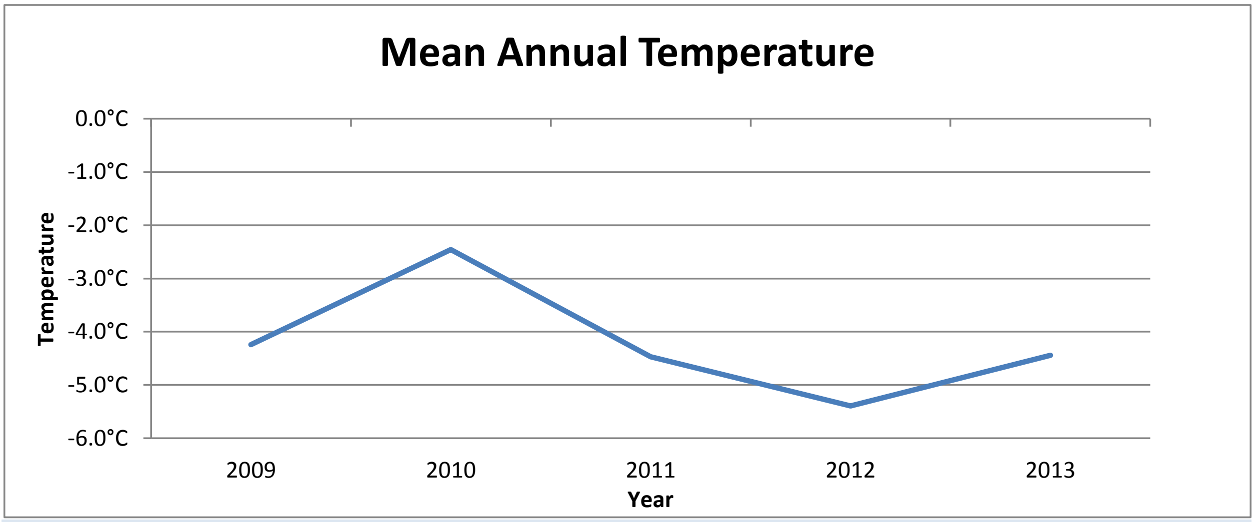


	Main Daily Maximum Temperature	Mean Daily Temperature
Summer 2009	20.8°C	12.8°C
Summer 2010	20.6°C	13.3°C
Summer 2011	19.7°C	12.8°C
Summer 2012	19.9°C	12.7°C
Summer 2013	20.9°C	13.4°C

Figure 3.11. Dawson Mean Daily Maximum in Summer for 2009-2014 period.

3.2.3. Mean Annual Temperature

The year 2010 ranked as the warmest year on record, together with 2005 and 1998, according to the World Meteorological Organization. The annual temperatures from Dawson similarly show that 2010 was the warmest year for the considered period, whereas 2012 was the coldest (figure 3.12). Between this two extreme years, 2009, 2011, and 2013 annual temperatures are similar within an interval of 0.3°C. The average mean annual temperature for the 2009-2013 period is -4.2°C. It can be expected than the ground temperature profiles recorded in 2010 should be the warmest, whereas the profiles recorded in 2012 should be the coldest.

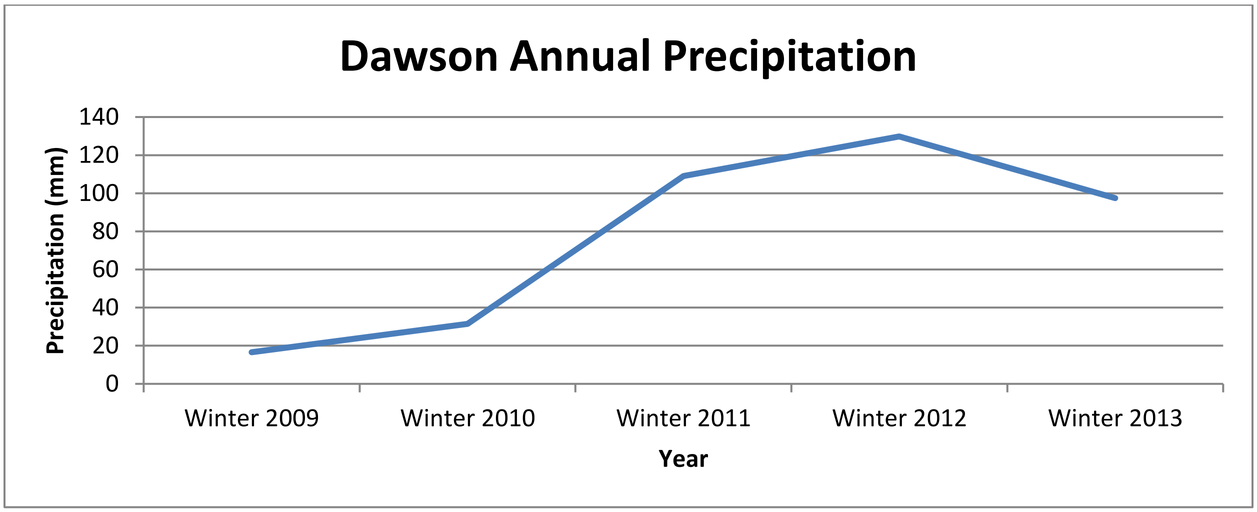


	Mean Annual Temperature	Main Annual Maximum Temperature	Mean Annual Minimum Temperature
2009	-4.2°C	2.2°C	-10.7°C
2010	-2.5°C	3.7°C	-8.6°C
2011	-4.5°C	1.8°C	-10.7°C
2012	-5.4°C	0.7°C	-11.5°C
2013	-4.4°C	2.0°C	-10.9°C
Mean	**-4.2°C**	**2.1°C**	**-10.5°C**

Figure 3.12. Dawson Mean Annual Temperature for 1901-2009 and 1980-2009.

3.2.4. Total Winter Precipitation

The data provided by Environment Canada show an increase of precipitation during the winter for the 2009-2013 period. The highest precipitations are recorded in 2012, and the lowest in 2009. The precipitations observed in 2009 and 2010 appear to be surprisingly low; a problem with the station is not excluded. As the streets are cleared of the snow during the winter, the amount of winter precipitation should not impact the ground temperature profiles. Yet, a crust formed at the surface of the road that may have an impact. It has be reported that when a cold spell happens before the first snow precipitation occurs, buried pipes are more likely to break below the street of Dawson, whereas if a crust of snow has already formed on the street surface before the cold spell, break are less likely to occur (Norm Carlson, personal communication).

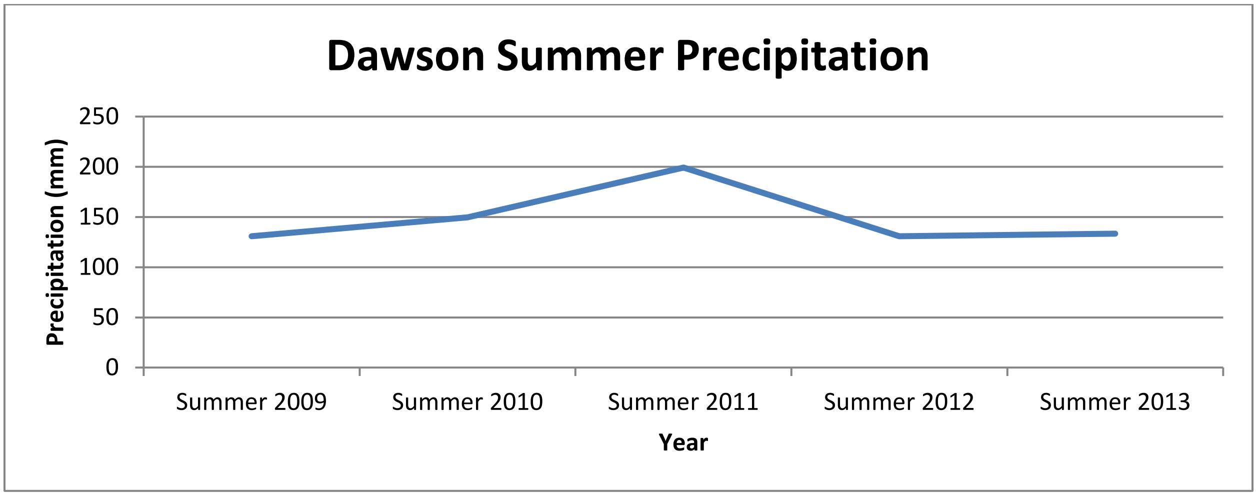


Row Labels	Total Precipitation (mm)
Winter 2009	16.6
Winter 2010	31.5
Winter 2011	109
Winter 2012	129.8
Winter 2013	97.4
Grand Total	**384.3**

Figure 3.13. Total Winter Precipitation for the 2009-2013 period.

3.2.5. Total Summer Precipitation

The data provided by Environment Canada show that Dawson summer precipitations had a peak in 2011 with 199 mm, whereas they range from 139 to 150 for the four remaining years. Generally, wetter condition is more likely to warm permafrost temperature.

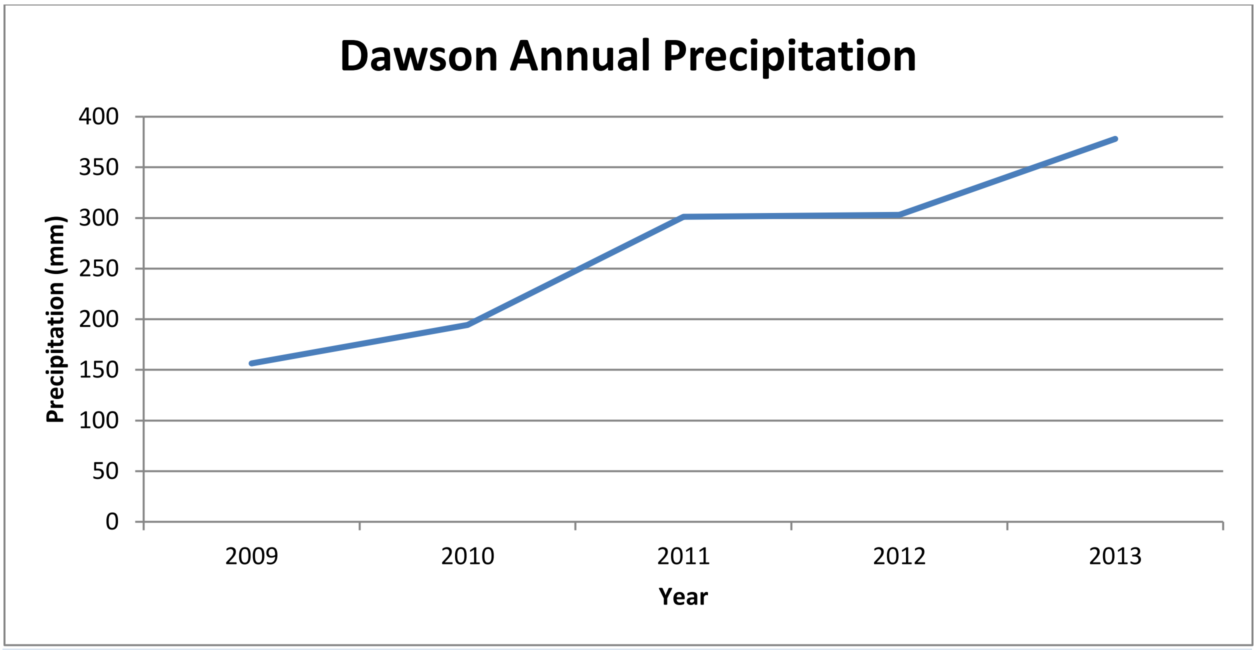


	Total Precipitation (mm)
Summer 2009	130.8
Summer 2010	149.6
Summer 2011	199.2
Summer 2012	130.8
Summer 2013	133.4
Grand Total	**743.8**

Figure 3.14. Total Summer Precipitation for the 2009-2013 period.

3.2.6. Total Annual Precipitation.

The data provided by Environment Canada show an increase of precipitation from 2009 to 2013. This is more likely related to the low winter precipitation recorded in 2009 and 2010 (section 3.2.4). If the trend is real, and not attributable to a problem of data acquisition, the wetter conditions are more likely to contribute to the warming of permafrost temperature below Front Street during the 5-year period.

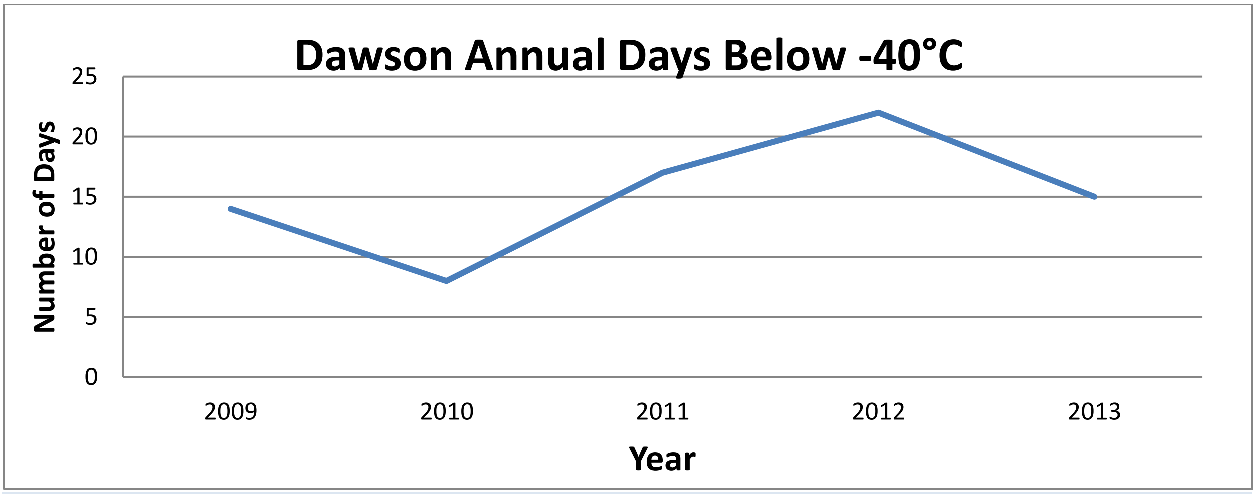


Row Labels	Total Precipitation (mm)
2009	156.4
2010	194.4
2011	301.2
2012	303.1
2013	378.1
Grand Total	**1333.2**

Figure 3.15. Total Annual Precipitation for the 2009-2013 period.

3.2.7. Days Below –40 C.

The year 2010 has the lowest number of annual days below -40°C. This is not surprising considering that 2010 is one of the warmest years since climatic records exist. The year 2012 has the highest number that is consistent with the mean annual temperature values. This reinforces the idea that it should be expected that ground temperature records should be warmer in 2010 and colder in 2012.

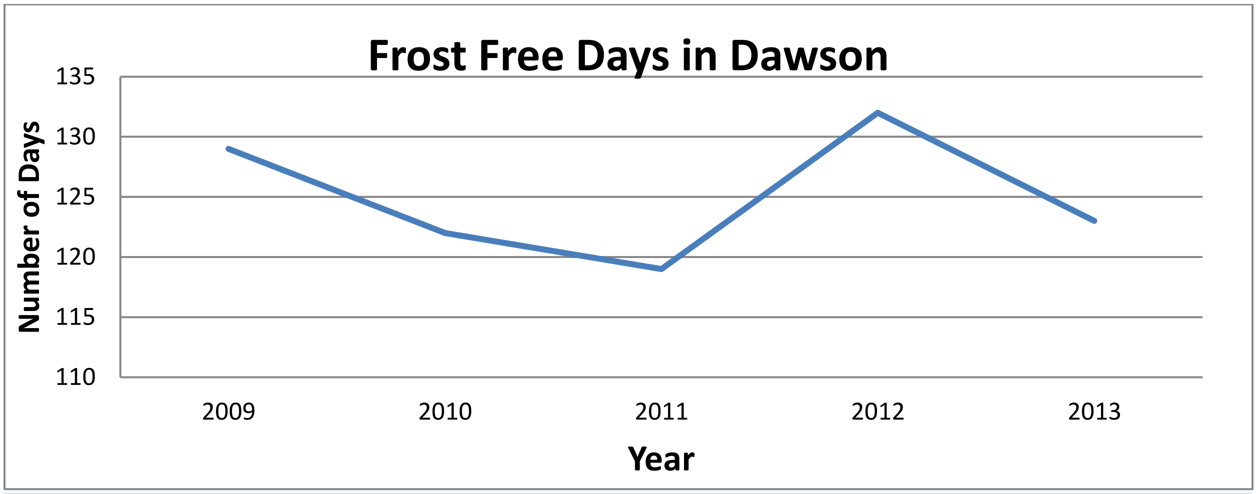


Row Labels	Days Below -40°C (°C)
2009	14
2010	8
2011	17
2012	22
2013	15
Grand Total	**76**

Figure 3.16. Days Below –40°C for the 2009-2013 period.

3.2.8. Frost-Free Days.

The year 2012 appears to have the greater number of frost free days in Dawson, and 2011 is the year having the lower number. This result seems counterintuitive as 2012 is the coldest year of the period.



Row Labels	Count of Min Temp (°C)
2009	129
2010	122
2011	119
2012	132
2013	123
Grand Total	**625**

Figure 3.17. Frost-Free Days for the 2009-2013 period.

4. Ground Temperature records

4.1. The data set and its limitation

The figure 4.1 presents the available ground temperature data that were recorded below Front Street. Following the circumstances explained in section 1.1, the dataset is incomplete, and pitted with numerous gaps. This is the first limitation in term of analysis.

Without continuous record, it is hard to distinct any trend within the record. Comparison can be carried following two approaches. The first one consists in comparing data within a same series, i.e. comparing temperatures for a same station, and a same period of the year, but for different successive years. These periods are shown in the green rectangles for each station in figure 4.1. This type of comparison allows assessing the influence of the climate on the ground temperature of a single station. Looking at the dataset, such comparison can only be done, in some limited extent, for station Gray, Ivory, and Gold. The most appropriate station for multi-year comparison is Gray, because it has at list two full yearly cycles; yet another limitation rose later during the analyses due to the 2012 logger replacement. The second type of comparison consists in comparing data collected at same time for different stations. These periods are shown in red rectangle in figure 4.1. This type of comparison allows discriminating the site-specific factors that may influence the ground temperature regime. Only the period of Summer 2012 allows to compare all four ground temperature regime, while the period of 2009 allows to compare only three stations (Gray, Ivory, and Gold).

A second type of limitation was coming from the fact that some of the loggers where logging data in an erratic way. Each few days, on reading was missed and resulted in 5 reading per day instead of six. Also, sometimes, an additional reading was performed resulting in 7 readings a day instead of six. These erratic logging events had to be identified to allow processing the data under Excel. After scrutinizing the dataset, excess data were removed, and blanks were filled with an average of the previous and following temperatures.

Finally, a third type of limitations appeared when analyzing the temperatures recorded buy the third set of logger that was installed during fall 2012. An off-set appeared in the recorded temperatures, the new recorded temperature appearing colder than the former ones. To compensate the off-set, each new temperature was corrected based on the difference of temperature at the deepest sensor (Figure 4.2). For example, the temperature at Gray, at 5 m depth, was -0.5°C on September 27th 2012. The temperature recorded at the same depth with the new logger was -2.1°C on October 9th 2012, only 12 days later, while at this depth, the temperature should be relatively stable at this time of the year, as proven by previous record. Consequently a correction of +1.6°C was applied at all new recorded temperature at Gray Station. A correction of +1.6°C was also applied at Ivory Station, as a similar offset was observed.

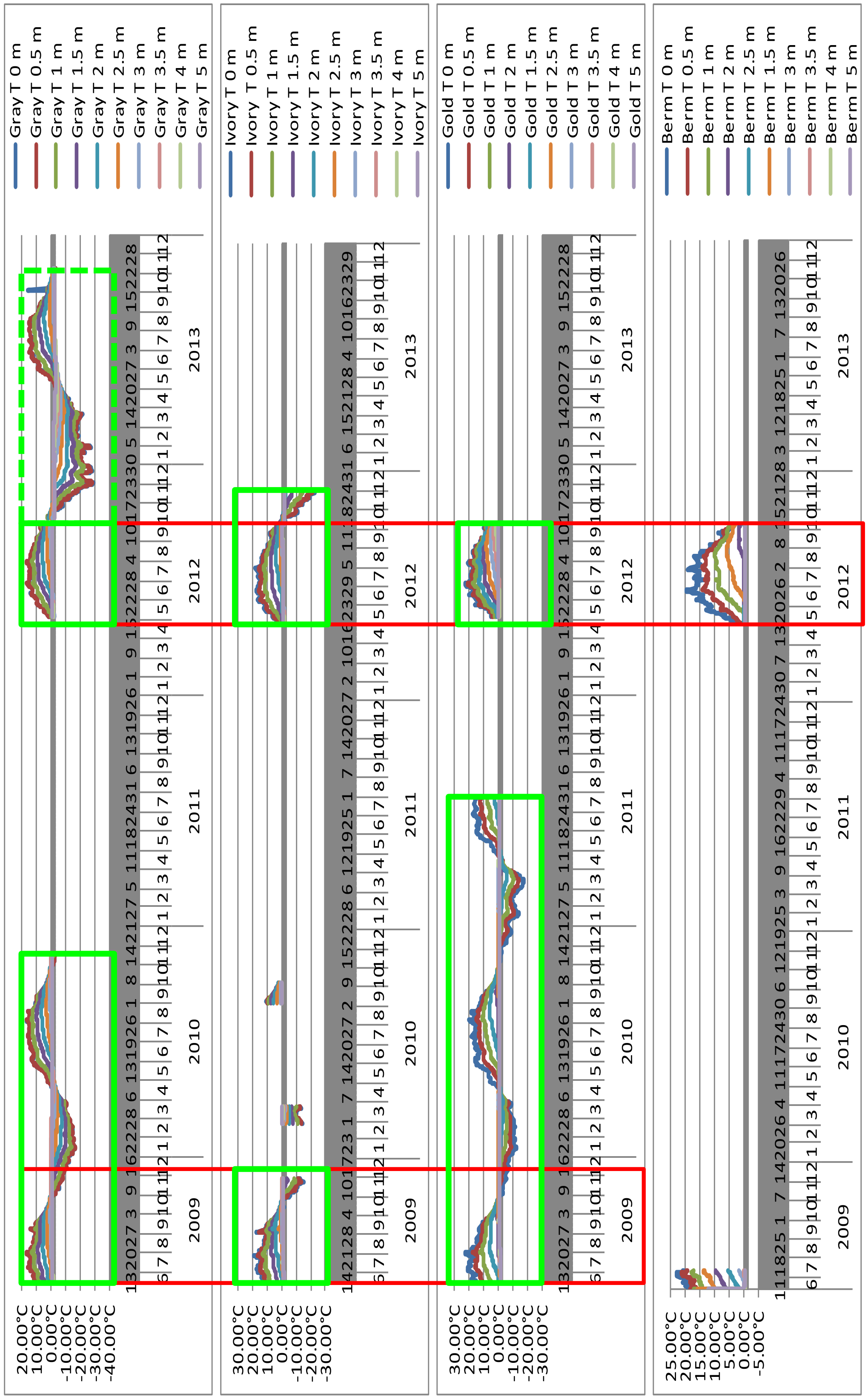


Figure 4.1. Ground Temperature Dataset from Front Street

In many case, the source files from the logger were not provided. The analyses were performed from record files that may have been incomplete and, in some case, altered. As the history of the dataset is unknown, in addition to all previous consideration, all interpretations originating from the dataset have to be considered with caution.

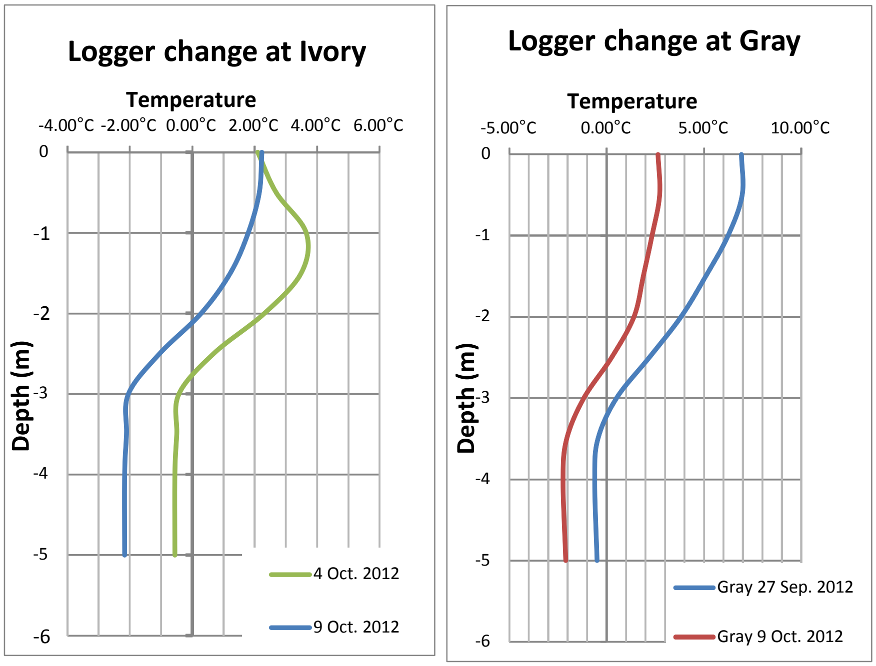


Figure 4.2. Off-set observed in ground temperature profile after logger shifts.

4.2. Thaw Front

The observation of the depth of the seasonal thaw front from year to year in a good way to monitor the effect of yearly variation of climate and surficial conditions on permafrost.

The table 4.1 show the thaw front measured for each station, based on the ground temperature records, whereas figure 4.2 show the ground temperature profile measured for each station at the time of the deepest thaw front for each year.

	Thaw Depth (m)				
Year	2009	2010	2011	2012	2013
Gray	-3.31 (29 Sep)	-3.36 (25 Sep)		-3.28 (22 Sep)	-3.17 (19 Sep)
Ivory	-3.02 (10 Sep)			-2.83 (11 Sep)	
Gold	-2.31 (25 Sep)	-2.39 (17 Sep)		-4.89 (28 Sep)	
Berm				-2.42 (06 Sep)	
Mean Annual Temperature	-4.2°C	-2.5°C	-4.5°C	-5.4°C	-4.4°C
Summer Mean Daily Temperature	12.8°C	13.3°C	12.8°C	12.7°C	13.4°C
Summer Mean Maximum Daily Temperature	20.8°C	20.6°C	19.7°C	19.9°C	20.9°C

Table 4.1. Thaw fronts measured from ground temperature profiles.

The thaw front at GRAY station was 3.31 m deep in 2009, at the time of the lift of the new pavement. It was 3.36 m deep in 2010, during the warmest year of the period, and 3.28 m deep during the coldest year of the period. Based on these observations, we can assume that the paving work of 2009 did not impacted permafrost at this location. In 2013, the thaw front (based on temperatures that were corrected from the logger offset) was slightly less deep, at 3.17 m. As there is no significant difference between Summer Mean Daily Temperature for each year of the period, and there is only a 8 cm difference between the thaw fronts for the hottest and coldest years, it can be assumed that the active layer has become thinner during the period under the influence of the new pavement.

The depth of the thaw front at IVORY was 3.02 m in 2009 when the street was freshly paved. It was 2.83 m three years later, in 2012. Without any other measurement, it is difficult to affirm that the decrease of active layer thickness is solely related to the implementation of the white pavement; yet this hypothesis remains plausible even if 2012 was the coldest year.

The depth of the thaw front at GOLD was 2.31 m in 2009, after Front Street was paved. It was 2.39 m, slightly deeper, in 2010; and then the thaw front reached 4.89 m in 2012, which is a major increase. Based on the log description (Figure 2.5), the thaw front even propagated through the silt layer beginning at 2.5 m depth. Figure 4.3 show the evolution of the thaw front recorded between May 7th and September 29th 2012; only the deepest sensor at 5 m depth remained frozen at the end of September. GOLD and IVORY share similarities in term stratigraphy: the layer of silt occurs at 2.5 m depth at both sites. Then it can be assumed that the cause of the deepening of the active layer is not related to the geology. A possible explanation is that an underground spring may have flown nearby GOLD location when Spring time came, and that accelerated the progression of the thaw front.

Only one value of thaw front depth is available for the BERM station. This value is the shallowest for the four stations at the time of the measurement. This could be due to the fact that the upper layer of silty sand fill is thicker than in any other station (figure 2.5), the silty gravel layer being encountered at 2.8 m depth. The finer sediment may contain more water en require more energy to thaw than at the other sites.

When comparing the thaw fronts of each borehole with the others, it seems that the deepest thaw fronts are occurring in the southern section of the street, whereas the thinner ones are present in the northern section. As discussed in section 4, the northern area of the city is reputed to have higher ground ice content than the southern area. This may explain thinner active layer, at more energy is thaw ice richer sediment because this material has higher latent heat.

With the exception of GOLD, the other stations seems to have experience at thinning of their active layers during the 2009-2013 period.

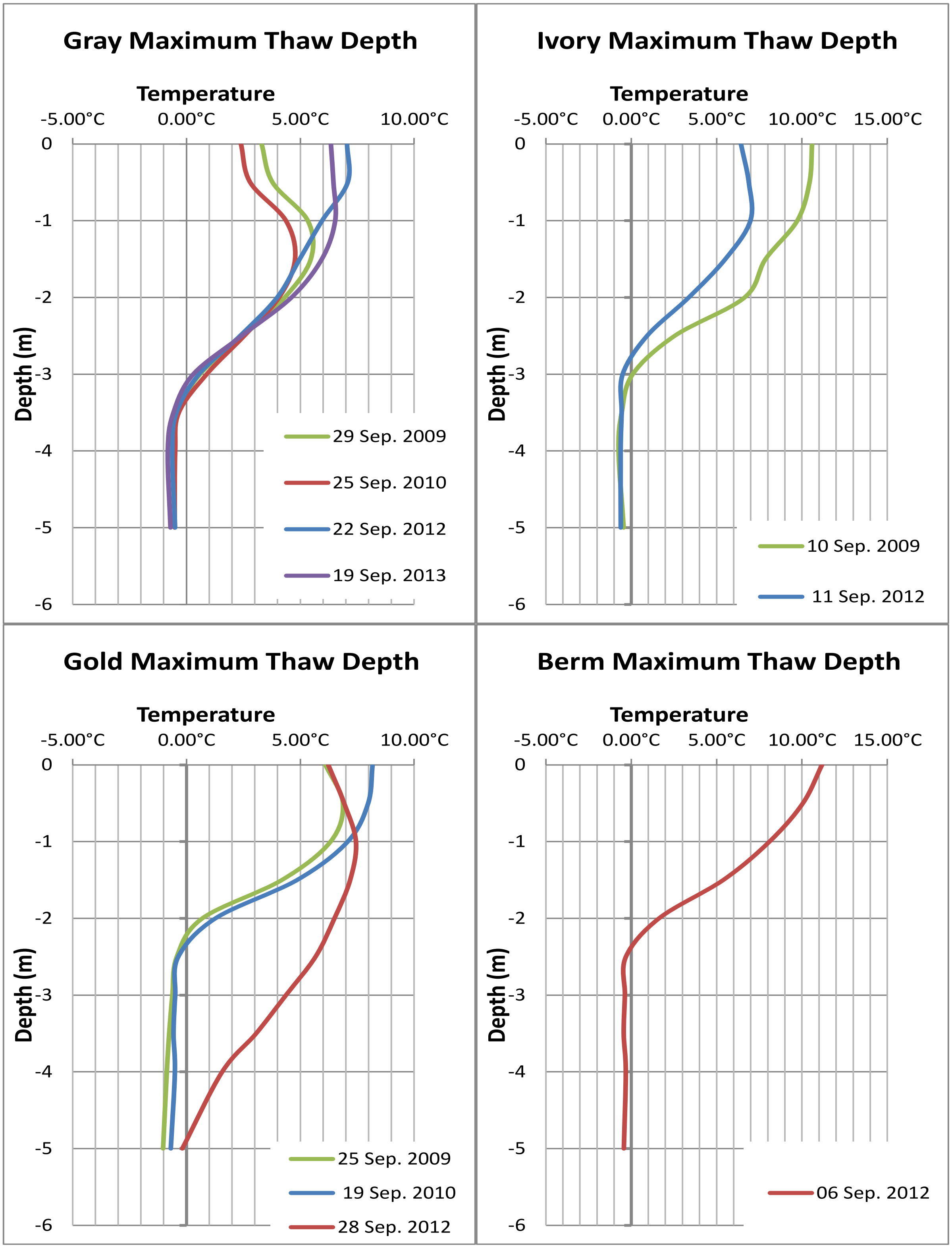


Figure 4.2. Ground temperature profile at the days of the deepest thaw front values

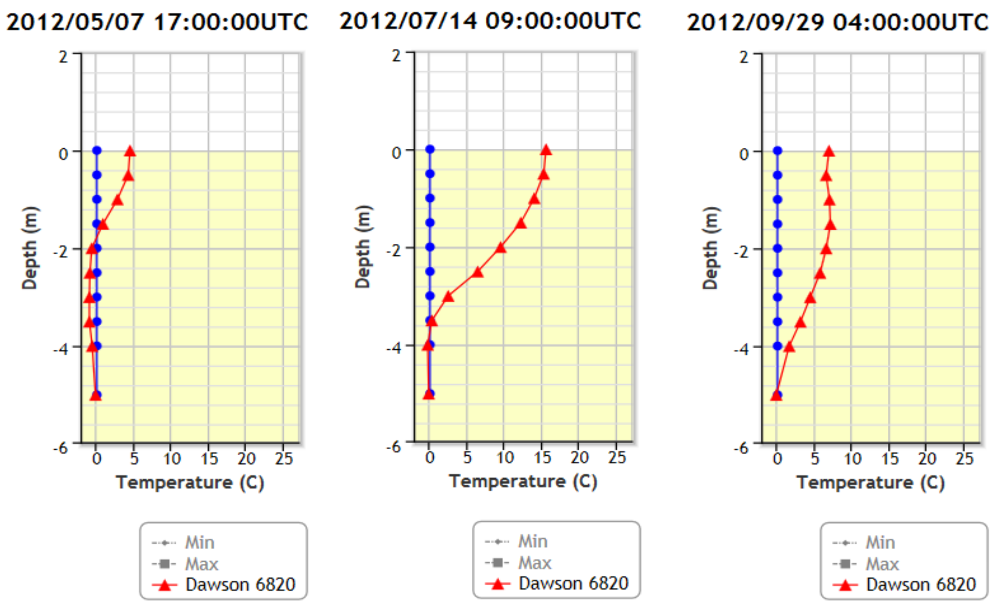


Figure 4.3. Ground Temperature profile from the loaned logger at Gold May-September 2012

4.3. Permafrost Temperature

Table 4.2 show the monthly mean ground temperature at 5 m depth available for all station. The mean monthly values that are shown in red are calculated from incomplete record because the loggers either started or stopped during in the considered month. In this table, only the deepest temperatures, at 5 m, are shown because there are the most stable ground temperatures, and therefore the more likely to be representative of the permafrost thermal regime from a long term perspective.

All stations display warm ground temperature mostly around -0.5°C. GRAY has the coolest temperature, down to -1.42°C in July 2012, whereas GOLD has the warmest ones, at -0.18°C from May to September 2012. This two boreholes have an opposite trend along time, as GRAY seems to become colder, and GOLD seems to become warmer. If the warming of GOLD seems undeniable, the trend is less clear for GRAY, as temperature seems very similar except for the 2013 records. Based on the few recording available for IVORY, it is possible that a slight warming has occurred between 2009 and 2012. Finally, the very incomplete data available for BERM would suggest a slight cooling between 2009 and 2012. The trends observed from the 5 meter deep temperature seems inconclusive.

Four “trumpet curves” permafrost graph can be produces from the dataset (Figure 4.4). Two graphs can be made for GRAY, one from July 1st 2009 to June 30th 2010, and the second from July 1st 2012 to June 30th 2012. The two other graphs are made from GOLD station, the first from July 1st 2009 to June 30th 2010, and the second from July 1st 2010 to June 30th 2011.

	Gray T 5 m	Ivory T 5 m	Gold T 5 m	Berm T5 m
2009	**-0.58°C**	**-0.99°C**	**-1.11°C**	**0.11°C**
June	*-0.85°C*	*-1.54°C*	*-1.62°C*	*0.35°C*
July	-0.71°C	-1.27°C	-1.42°C	*-0.31°C*
August	-0.61°C	-1.04°C	-1.23°C	
September	-0.55°C	-0.84°C	-1.06°C	
October	-0.51°C	-0.76°C	-0.96°C	
November	-0.48°C	*-0.68°C*	-0.87°C	
December	-0.45°C		-0.81°C	
2010	**-0.53°C**	**-0.54°C**	**-0.69°C**	
January	-0.45°C		-0.75°C	
February	-0.44°C	*-0.53°C*	-0.72°C	
March	-0.44°C	*-0.55°C*	-0.69°C	
April	-0.48°C		-0.69°C	
May	-0.61°C		-0.69°C	
June	-0.63°C		-0.69°C	
July	-0.63°C		-0.69°C	
August	-0.57°C		-0.69°C	
September	-0.55°C		-0.69°C	
October	-0.51°C		-0.69°C	
November	*-0.51°C*		-0.65°C	
December			-0.63°C	
2011			**-0.63°C**	
January			-0.63°C	
February			-0.63°C	
March			-0.62°C	
April			-0.60°C	
May			-0.62°C	
June			-0.65°C	
July			*-0.68°C*	
2012	**-0.52°C**	**-0.69°C**	**-0.18°C**	**-0.44°C**
May	*-0.56°C*	*-0.97°C*	*-0.18°C*	*-0.44°C*
June	-0.62°C	-0.86°C	-0.18°C	-0.43°C
July	-0.57°C	-0.74°C	-0.18°C	-0.44°C
August	-0.54°C	-0.65°C	-0.18°C	-0.44°C
September	*-0.50°C*	-0.58°C	*-0.18°C*	-0.44°C
October	*-0.46°C*	-0.54°C		*-0.45°C*
November	-0.45°C			
December	-0.44°C			
2013	**-0.82°C**			
January	-0.41°C			
February	-0.39°C			
March	-0.49°C			
April	-1.03°C			
May	-1.42°C			
June	-1.28°C			
July	-1.01°C			
August	-0.82°C			
September	-0.71°C			

Table 4.2. Monthly Mean Ground temperature at 5 m depth.
Red number are mean value from incomplete monthly records.

The permafrost trumpet graphs shows three curves: the minimum monthly mean temperature, the maximum monthly mean temperature, and the mean Annual ground temperature profiles. Usually, this type of graph covers one full yearly cycle, from January 1st to December 31st; but to be able to make comparison that won't be possible otherwise, a yearly July to June cycle was chosen.

GRAY graphs (figure 4.4 upper graphs) show a very warm mean annual temperature for 2009-2010 with values close to 0°C, and a mean annual temperature of -0.53°C at 5 m depth. Three years later, for 2012-2013, the ground temperature seems to have cooled down, with a mean annual temperature of -0.67°C at 5 m depth. The mean annual curve show a trend to cooling. It seems mostly attributable to winter temperature as the minimum curve has cooled, whereas the maximum temperature curves remain very alike.

Between 2009-2010 and 2010-2011, GOLD graphs (figure 4.4 lower graphs) show a cooling trend for the upper part of the profile, and a warming trend in the lower part, below 2.5 m. As for GRAY, the minimum monthly mean temperature curves show a cooling, whereas the maximum monthly mean temperature remain unchanged.

The dataset also allow to perform comparison between summer ground temperature for 3 station (GRAY, IVORY, and GOLD) in 2009, from July to October (Figure 4.5 upper graphs), and for all 4 stations in 2012, from June to August. When comparing the profiles for each station in 2009, it appears that near-surface ground temperatures are similar for GRAY and IVORY with little more than 1°C difference. Gold temperatures are much similar too, except for July that is about 5°C warmer that at the other sites. This difference is hard to explain. A possible explanation could be related to exposure to the sun: Gold is located in front of vacant lot and does not beneficiate from the shade provided by a building at this time of the year like at GRAY and IVORY. When looking at the graphs from 2012, GRAY, IVORY, and BERM all share the same range of near-surface ground temperatures from June to August, between about 10 and 15°C. Once again, near-surface ground temperatures at GOLD are about 5°C above the other stations for June and July but not for august. June and July being the months where the sun is the highest in the sky, it would reinforce the exposure as explanation for these higher temperatures. The comparison between GOLD's profile of 2009 and 2012 confirms the strong increasing of active layer thickness.

Figure 4.6 shows a comparison between ground temperature profiles of July and August 2009, and July and August 2012, for GRAY, IVORY, and GOLD Station. At GRAY, 2012 profiles are slightly warmer. The difference is less evident for IVORY. In Gold, even if near-surface ground temperatures are relatively similar between 2009 and 2012, deeper temperatures differ significantly, as already discussed.

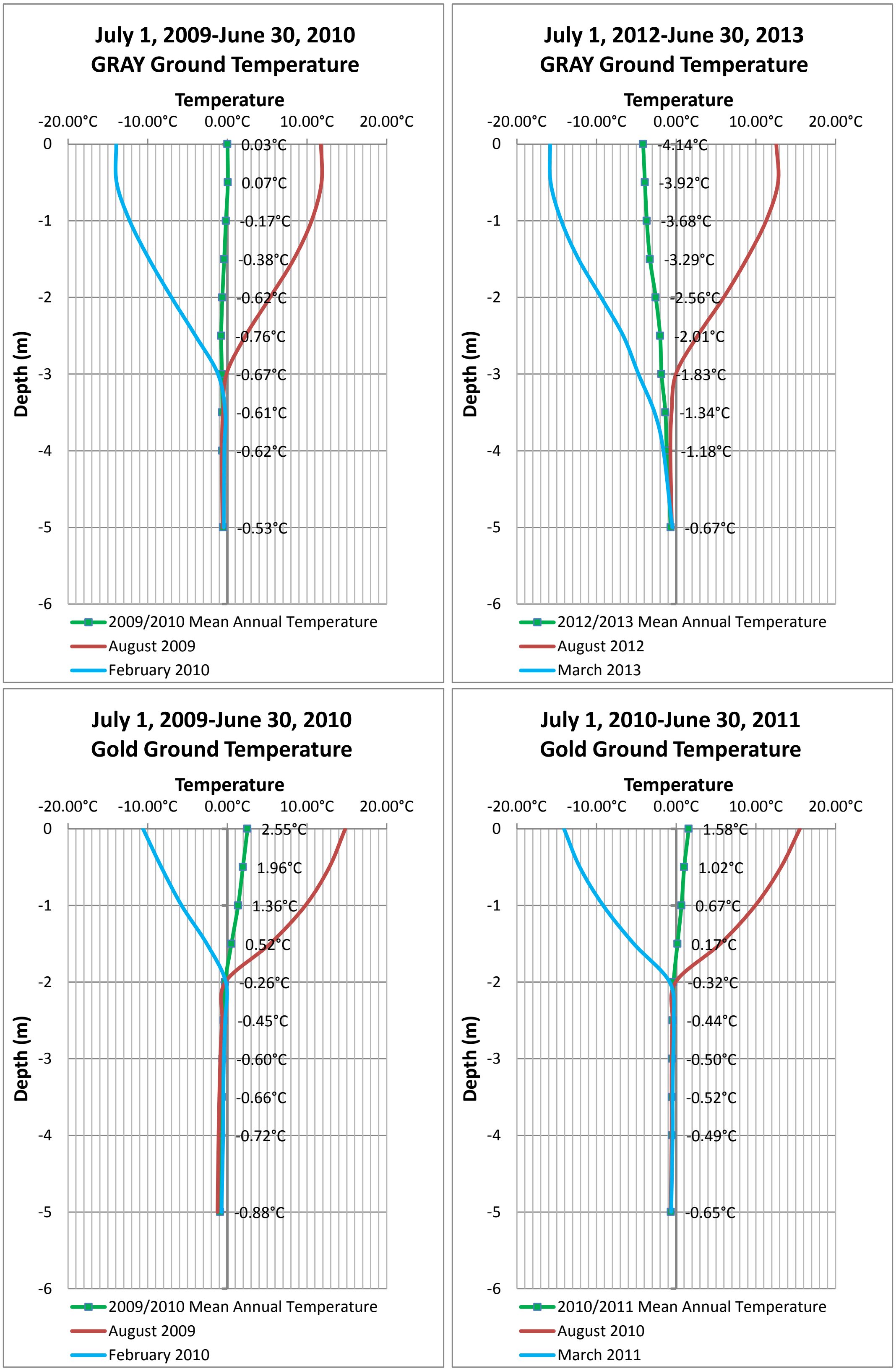


Figure 4.4. Permafrost graphs for GRAY and GOLD stations.

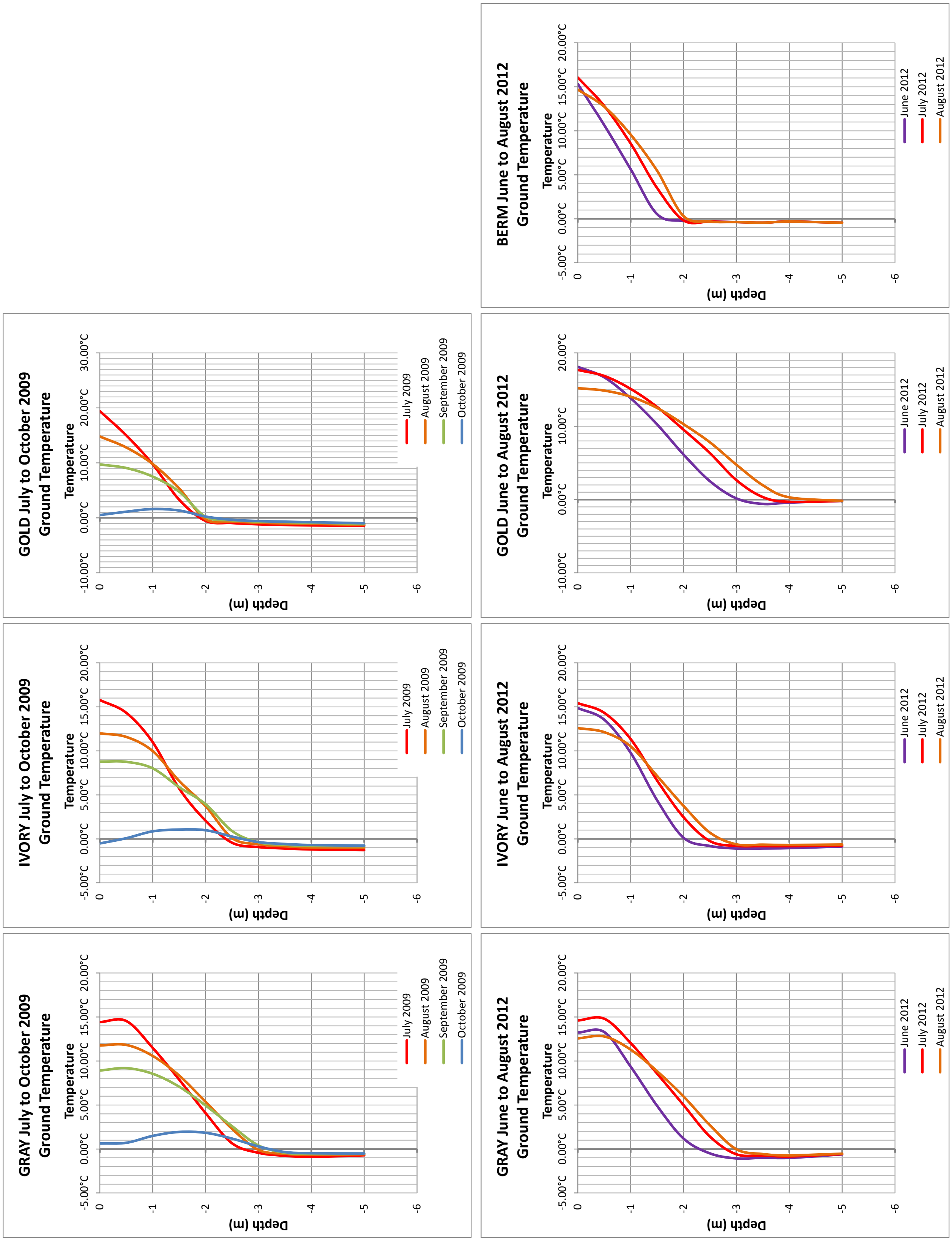


Figure 4.5. Ground temperature profile for summer months in 2009 and 2012.

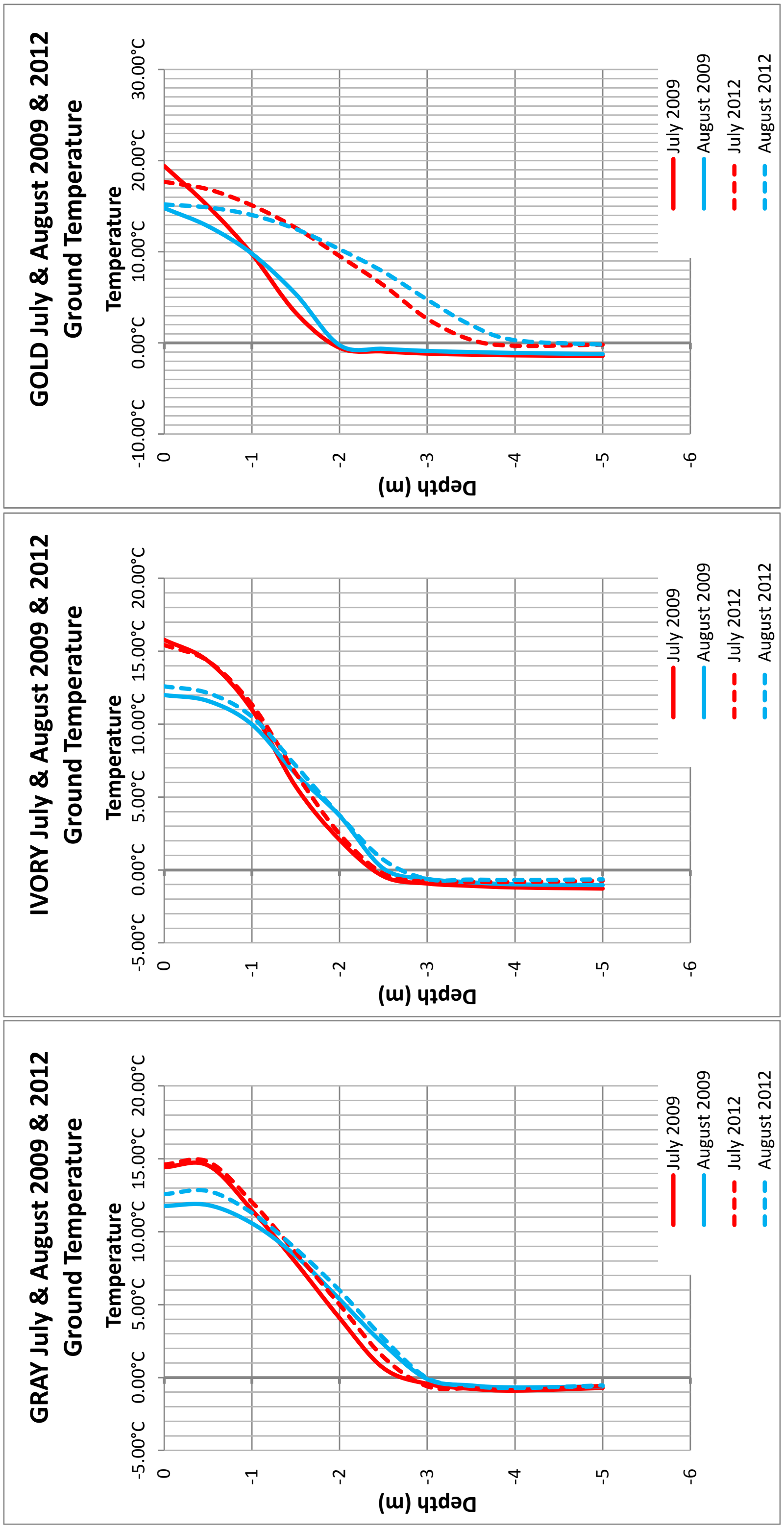
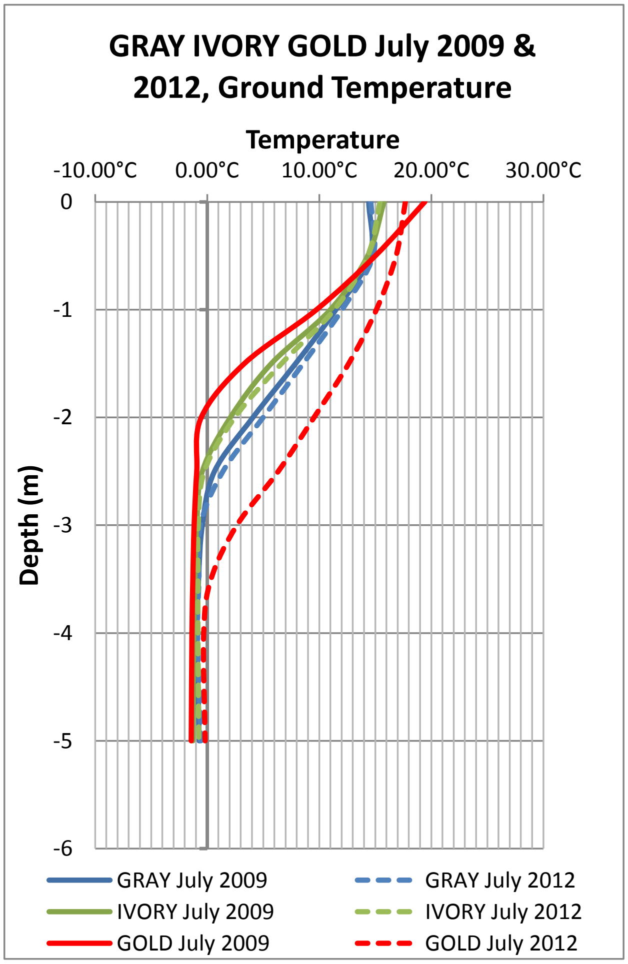


Figure 4.6. Ground temperature profiles for July-August 2009 and 2012, for GRAY, IVORY, and GOLF stations.

The figure 4.7 shows the ground temperature profiles for GRAY, IVORY, and GOLD in July 2009 and 2012, and in August 2009 and 2012 separately. These graphs allow seeing that in 2009, during the summer, GOLD had the coldest profiles and GRAY had the warmest, IVORY being in-between. In 2012, all profiles seem warmer, GOLD becoming the warmest, and IVORY the coldest of the three.



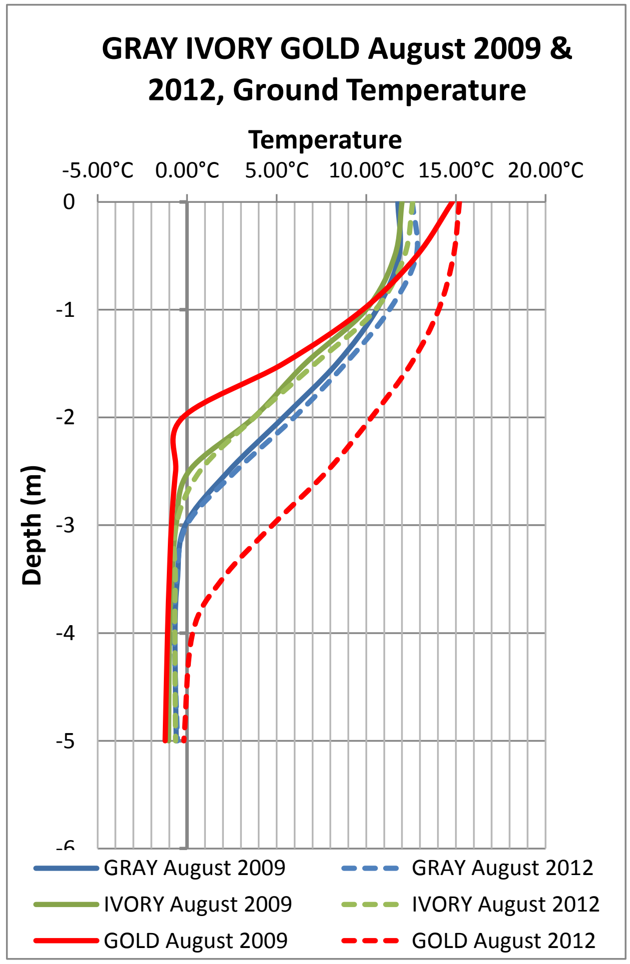


Figure 4.7. Ground temperature profiles for GRAY, IVORY, and GOLD in July 2009/2012, and in August 2009/2012

4.4. Synthesis

The dataset is impaired by 3 types of issues: gaps due to logger failures, erratic hourly logging, and temperature off between ancient at recently installed loggers.

The thaw appears to have slightly regressed at GRAY and IVORY stations, while it has increased at GOLD Station, maybe because of a ground water flow. The climate does not seem to be responsible for the variations observed. BERM station has the shallowest thaw front, maybe because it could have higher frozen water content. In general, Thaw fronts to go deeper in the southern sites.

The mean permafrost ground temperatures at 5 m depth are around -0.5°C, GRAY being the coldest, around -0.9°C, and GOLD the warmest, around -0.2°C. GOLD's temperatures have grown warmer overtime since 2009.

Trumpet graphs for Gray shows a cooling between 2009 and 2013. GOLD'S graph show a mixt evolution between 2009 and 2011, with a cooling in the upper section of the profile and a warming in the lower section, prior to the general warming event that was observed in 2012.

When comparing summer months ground temperature profile between stations for 2009 and 2012, GRAY, IVORY, and BERM stations appear to have similar trends for near-surface ground temperature, whereas GOLD appears to have warmer temperature, by 5°C, in June and July. This may be due to a different exposure to the sun than for other sites.

5. Recommendations for potential follow-up work.

The recommendations in this section address three general issues: data acquisition, data treatment, and supplementary data that would benefit to the project.

5.1. Data Acquisition: Logging and Downloading

The prevent logger failing and ensure data quality, a regular maintenance routine should be established. As such routine seems difficult to implement by HPW Yukon, it is suggest that contact are made to develop a collaboration with the Public Work department of Dawson City or other organism interested in the matter.

The station should be visited two times per year, ideally, early spring and late fall.
Spring visit should include: logger inspection for good working order, battery Check, and data downloading.
Fall visit should include: logger inspection for good working order, mandatory battery replacement, and data downloading.

5.2. Data treatment: management and formatting:

A data base should be created only dedicated for front street data. The data base should include:

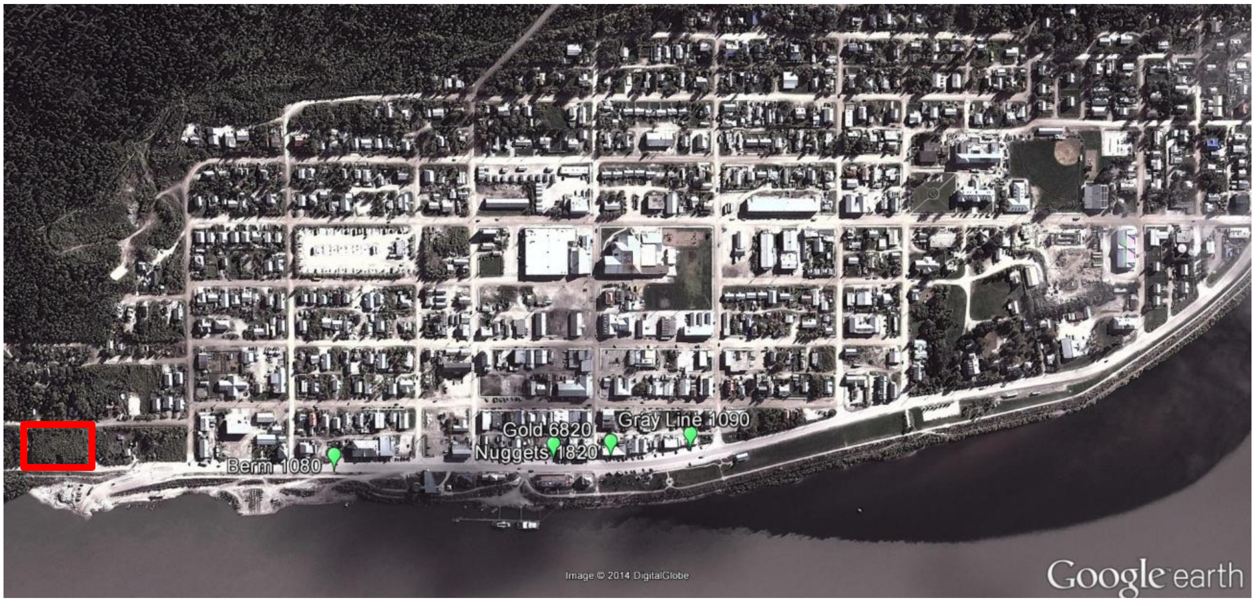
- A subfolder to archive the original logger files by date of downloading.
- A subfolder to archive the logger files converted in Excel format by date of downloading. Data should be check and any error corrected before Copy and Paste into Formatting Excel file.
- A subfolder to archive the Formatting Excel files, ideally, one file per logger per year.

Ideally, the Formatting files should be pre-formatted to automatically process graphs onto Copy and Paste action in a spreadsheet. Table and graph should be automatically generated through pre-established Pivot Tables. This should simplify reporting and data interpretation. Other Formatting Excel files merging boreholes and years should be considered.

5.3. Supplementary data

:
-1 witness site recording temperature a road section with BTS:
Comparison between BST and Biticular Pavement.

1 Witness site with undisturbed permafrost.
including air temperature recording.
To distinguish effects of the climate from effects of the pavement.



Gold 6820
Gray Line 1090
Nuggets 1820
Berm 1080
Image © 2014 DigitalGlobe
Google earth

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