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Climate change and permafrost stability in the eastern Canada Cordillera: The results of 33 years of measurements

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ABSTRACT

Over the last 33 years, a network of climate stations has been set up at high altitude mountain permafrost sites from Plateau Mountain near Claresholm, Alberta, north to Sheldon Lake on the North Canol Road in the Yukon. Taken together with the data from the US National Weather Service and the Canadian Atmospheric Environment Service, the results indicate a cooling of mean annual air temperature south of Calgary, no significant change in Calgary, a slight warming at Jasper, and a major warming at Summit Lake, west of Fort Nelson. In contrast, the south eastern and central Yukon show only a minor warming trend that lies well within the limits of a sixty-year record measured by the Canadian Atmospheric Environment Service. Along the Mackenzie valley and on the North Slope of Alaska, the mean annual air temperature is rising. Permafrost is aggrading on Plateau Mountain, degrading at Summit Lake, and appears to be stable in southern Yukon and southern Alaska. This is in contrast to the warming occurring on the Arctic coastal plain and along the Mackenzie valley. It therefore appears that changes in climate vary considerably from place to place, and even where warming may occur, it may not continue indefinitely. There has been a northward shift of the arctic front due to a weakening of air pressure in the Yukon and Alaska relative to the continental tropical (cT) and maritime polar (mT) air masses to the south. Any actual changes that may be occurring appear to undergo amplification along the Mackenzie valley and Arctic coastal plain and reduction by buffering in the interior Yukon and Alaskan mountains, a result of micro-environmental factors. Continued, careful monitoring of the climate is required and needs to be expanded in the National Parks in the mountains in order to provide data on the changes that may be taking place. Such measurements can provide a sound basis for interpreting ecological and other climate-related data. The existing climate models are not working satisfactorily because we do not know enough about the causes and processes involved in climate change. Improved results can indicate where best to site structures such as pipelines so as to minimize maintenance costs. Models may also help explain why certain areas such as Beringia, which saw reduced climate change, acted as important refugia during the glaciations.

Keywords: permafrost; stability; long-term measurement; climate change; the Eastern Canada Cordillera

1. Introduction

The study of permafrost distribution in the Eastern Cordillera of the Rocky Mountains began in 1974, when weather stations equipped with Lambrecht monthly soil temperature recorders, together with ground temperature cables, were placed on mountain tops at key sites. There was no previous work on the climate at permafrost sites and the only permafrost map of Canada was by Brown (1967a). No other long-term weather stations were sited at high elevations in the mountains south of 60°N where permafrost occurs, hence the need to establish new observation sites. North of the 60° parallel, permafrost occurs in the valleys allowing available data from the government weather stations to be used. The results from the new weather stations proved invaluable in providing the first data on climate at sites with permafrost (Harris and Brown, 1978), and also enabled scientists to evaluate the effect of different depths of snow cover in this environment. This, in turn, led to the development of a method of predicting permafrost occurrence based on freezing and thawing indices (Harris, 1981).

The number of weather stations was expanded as the work progressed. After 1990, measurements using data loggers and thermistors gradually replaced the earlier methods, following a trial period in which the two methods were compared (Harris and Pedersen, 1995). The most important mountain permafrost weather stations are still in use, and this paper reports on the results of the work at those stations.

2. Past work

Since the field work began, the efforts of the International Permafrost Association to collect a data base on both active layer thickness (CALM) and climate and ground temperature data for permafrost sites around the world has encouraged interest in climate change. In addition, increased attention to "global warming" usually ascribed to the effects of increased levels of carbon dioxide in the atmosphere, has led to development of models illustrating its theoretical effects. The products from these models suggest that the area north of 60° latitude in the northern Cordillera should show the maximum effects of the warming (Anisimov and Poliakov, 2003).

An examination of the available climate data from the most reliable Government sources indicates that this is not so (Harris, 2006; 2007; 2008). Instead, the evidence suggests that the best available data from at least 50 percent of Alaska and 75 percent of the Yukon Territory do not show any strong warming trends (see also Sergeev, 2007), although marked warming is recorded by the same sources for the northern parts of Alaska and the Mackenzie valley (Osterkamp and Romanovsky, 1999; Kershaw, 2003). The climatic changes that are occurring vary greatly from place to place in the region.

In a study of the long-term records of air temperature from Calgary, Clark *et al*. (2000) found that the mean annual air temperature had not changed since 1950, although both the freezing and thawing indices had decreased. In another study using the available Atmospheric Environment Service data from western Canada, Nkemdirim and Budikova (2001) detected weak evidence that there had been changes in the relative strengths of the continental arctic (cA) / continental polar (cP) and continental tropical (cT) air masses affecting the region. These would result in a change of position of the northern jet stream. Sheridan (2003) has suggested that the strength of these air masses and their trajectories are related to the Pacific North America Pattern Indices (PNA). Accordingly, one of the first objectives of this paper is to determine what changes have occurred during the last 33 years south of the 60° parallel along the Eastern Cordillera where permafrost is found. South of the 60° parallel, government weather stations are mainly located in valleys and inhabited areas where they can be used to predict the daily weather, so that it is necessary to use weather stations specifically sited near the tops of the mountains, at or near permafrost sites, to determine what actual changes in mean annual air temperature (MAAT) may be taking place.

Any changes in climate potentially alter permafrost conditions (Brown and Péwé, 1973; Romanovsky *et al*., 2002) unless the temperature changes are offset by changes in precipitation or its timing (Sergeev, 2007). Thus a close relationship between the stability of the climate and the stability of permafrost would be expected at most sites. Zhang *et al*. (2006) noted the evidence of warming of the climate on the North Slope of Alaska as well as evidence of thawing of permafrost in Northern British Columbia, which has been interpreted as evidence that both climatic warming and permafrost degradation are occurring throughout the Western Cordillera (see also Clague, 2008). However, it is not that simple. For example, Harris (2006; 2007) found evidence that in the interior valleys of large areas of mountains in the northern Cordillera, a combination of cold air drainage, temperature inversions and steam fog may act to buffer the permafrost from the effects of changes in mean annual air temperatures. Brewer and Jin (2008) described evidence that in the arctic lowlands at Barrow, Alaska, there has not been an increase in thickness of the active layer of soil in spite of a warming of 2 °C in the last half century, even though the active layer is warmer.

3. Methods used

3.1. Measurement of air temperatures

Initially, Lambrecht monthly temperature recorders were deployed in Stevenson Screens. Above tree line, the recorders had to be placed on the ground in boxes made of western red cedar, weighted down with stones. The sensors were attached to vertical poles and were shielded by an inverted can painted white to reflect direct sunlight. Tests showed that the two methods of protecting the instruments gave comparable results. The main disadvantage was that the charts had to be changed each month, which limited how many and where the weather stations could be located.

A correction curve was constructed for each recorder by comparing the air temperature recorded on the chart with readings made electronically using YSI thermistors. The latter had been calibrated at the Physics Laboratory in Ottawa using a platinum thermistor. Five comparative measurements were made spanning 0 °C with an accuracy of 0.001°C, and then a regression line was used to provide the correction for the YSI thermistor.

After 1990, data loggers became available, and the Lakewood data loggers with calibrated YSI thermistors were chosen as the standard after tests of the available data loggers were carried out by the Alberta Research Council. Experiments comparing the results of the Lambrecht measurements and those using thermistors showed that the results were comparable as regards mean annual temperature (Harris and Pederson, 1995). The main difference is in the lower maximum and higher minimum air temperatures due to the insulating effect of the covering protecting the thermistors from moisture. However, these tend to cancel one another out in the course of a year of measurement. This problem will be encountered to varying degrees at all sites where the metal recorders used previously have been replaced by automatic stations.

The use of data loggers also permitted additional measurements such as rainfall, relative humidity, *etc*., and the network was expanded into the Yukon Territory. The resulting network of currently active stations is shown in Figure 1. Use of a second station nearby provided a backup to counter periodic loss of data when batteries or data loggers failed, or when skiers, snow-mobilers, hikers, animals, or little boys with guns interfered with the data collection. The weather stations and recording equipment were repaired or replaced on each visit as necessary, and the batteries changed for the data loggers. Measurements of air temperature were collected by the data loggers every 20 minutes, and the maximum, minimum and mean values were stored in the memory every 24 hours. Once a year, the data was downloaded into a portable computer. The sites remained in the same place throughout the study. In this way, a reasonably complete data set has been obtained.

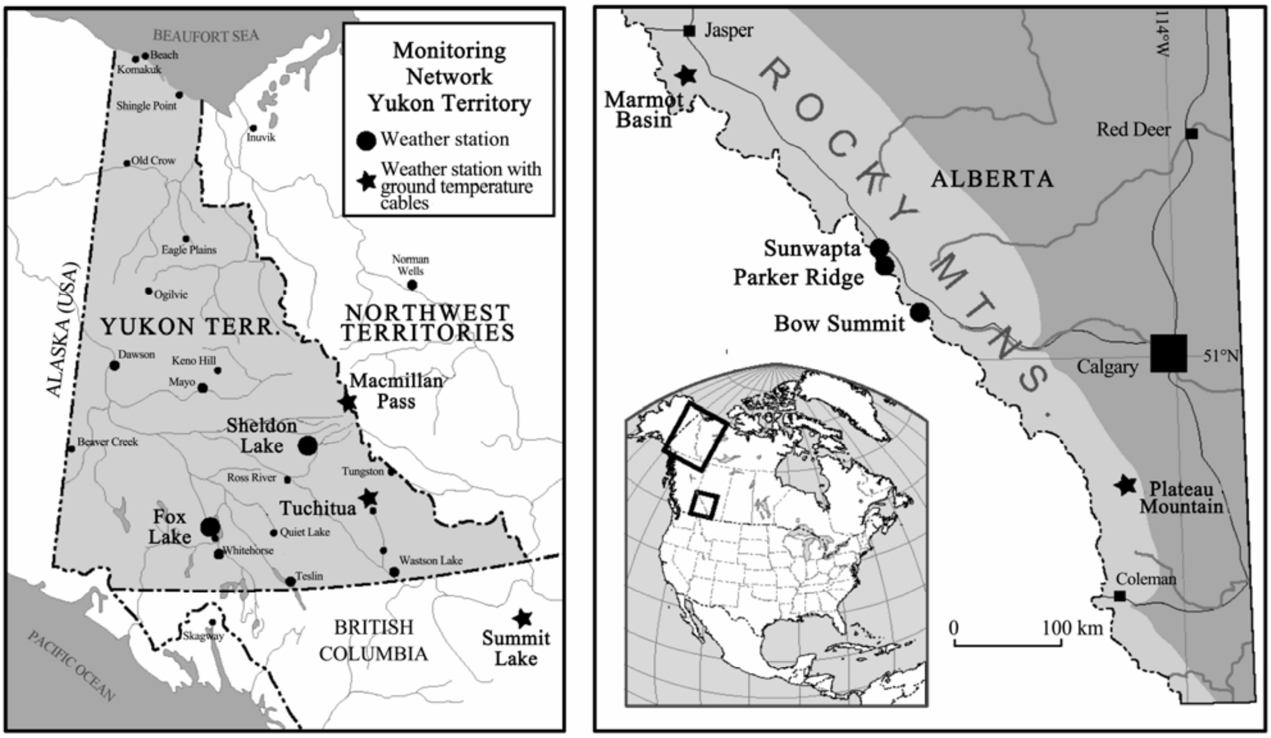


Figure 1 Location of the study sites maintained by the author along the Eastern Cordillera and in the Southern Yukon Territory and used in this paper.

3.2. Measurement of ground temperatures

South of the 60° parallel, measurement of ground temperatures was accomplished using YSI thermistor strings placed in holes drilled with a weasel-mounted rock drill (Harris and Brown, 1978). The ground temperature readings were made initially using a Wheatstone bridge during the monthly visits. Once data loggers were available, measurements were made by the data loggers every 12 hours and the readings downloaded once a year.

In the Yukon Territory, drilling was accomplished by using a hot-water drill in peat or silty sediments, by coring with an auger or by percussion augering. The sites were always close to water so the drill holes were cased using steel or plastic casing, inside which the thermistor string was placed. Comparative experiments showed that there was negligible conduction along the casing. The individual thermistors were checked against the calibrated thermistors, and the top of the casing was made so that it could be removed when necessary for checking or for replacement of the thermistor cables. A portable string of calibrated thermistors was used to check for any drift of readings with time.

3.3. Data handling

The results of the Lambrecht measurements of air temperatures were tabulated by hand as mean daily air temperatures for each station. Similarly, the monthly ground temperatures at each depth of measurement were recorded in tables. From these, the mean monthly and yearly air temperatures and the annual freezing and thawing indices could be calculated.

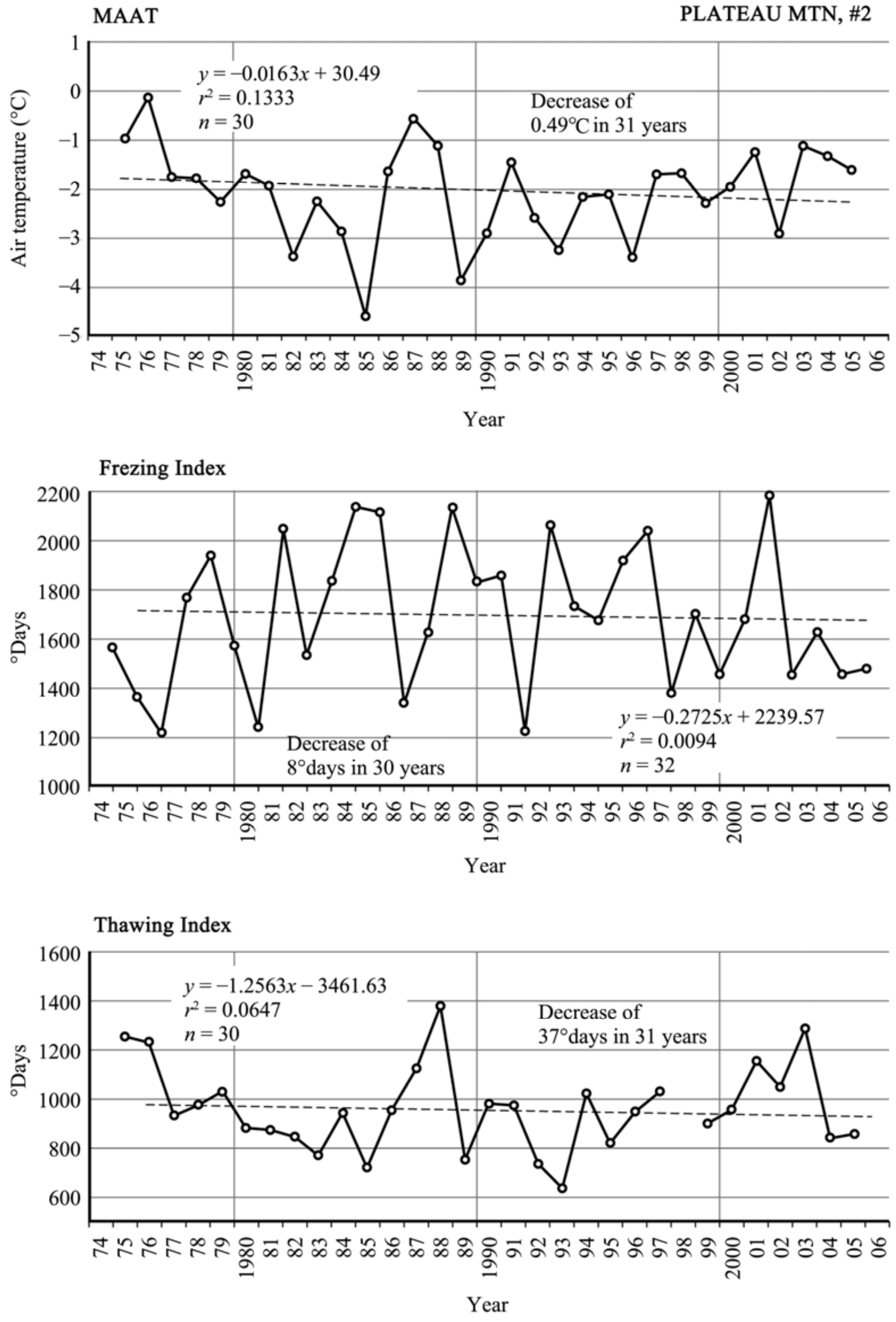


Figure 2 Changes in the MAAT, seasonal thawing index (STI), and seasonal freezing index (SFI) for Plateau Mountain #2 from 1974 to 2005.

The data from the data loggers posed a special problem. Due to the rapid evolution of computer operating systems and platforms during the period of the study, it was found to be impossible to store data in a systematic way using the electronic systems. The data loggers were designed to be programmed with a specific combination of platform-operating system and software which is now uncommon. This means it has been necessary to have dedicated computers to program and to remove the data from the data loggers. As a precaution against computer failure, the resulting climate data was manually transcribed as in the case of the Lambrecht and the manual observations.

For the purposes of this paper, three parameters are used for studying air temperature. The *mean annual air temperature* (MAAT) is the average temperature for the calendar year calculated from the mean daily air temperatures. The result is comparable to the balance in a bank statement. Large areas of western North America have a climate dominated by air masses. In order to understand their effects, this paper uses *seasonal freezing* and *thawing indices*. The *seasonal freezing index* (SFI) is the sum of the negative mean daily air temperatures for July 1st to June 30th, *i.e.*, it is a measure of the seasonal cooling during the winter from all sources, primarily the cA and cP air masses coming from the north. The *seasonal thawing index* (STI) is the sum of the positive mean daily temperatures for the calendar year (January 1st to December 31st). This is a measure of the seasonal warming by insolation, rainfall, mP air coming from the North Pacific Ocean, maritime tropical (mT) air from the central Pacific Ocean and by advection of hot cT air from the deserts of Arizona, Nevada, and California in summer. Together, these indices represent measures of the effects of the seasonal air masses controlling the climate of the region. Where the data for a month is missing, either the STI or the SFI may be calculated but not both. The mean annual air temperature for that calendar year will also be missing.

Linear regression lines are used to check for trends in the long-term data sets. Since there is substantial variability from month to month and year to year, the correlation coefficients are usually very low and cannot be interpreted as indicating reliability of the data. Rather, they indicate the degree of variation from year to year. Comparison of polynomial and linear regressions indicated a generally better correlation coefficient with the linear regression, probably due to the complexity of the yearly variations.

4. Results

The weather stations form a south to north transect along mountains of the Eastern Cordillera of the Rocky Mountains in Canada (Figure 1). The southernmost site is Plateau Mountain #2 (50°12′56.6″N, 114°37′W, 2,484 m) which shows a decrease in mean annual air temperature (MAAT) of 0.49 °C in 31 years (Figure 2). Both seasonal freezing (SFI) and thawing indices (STI) decreased but the seasonal thawing index decreased more. Note that the main change occurred before 1990.

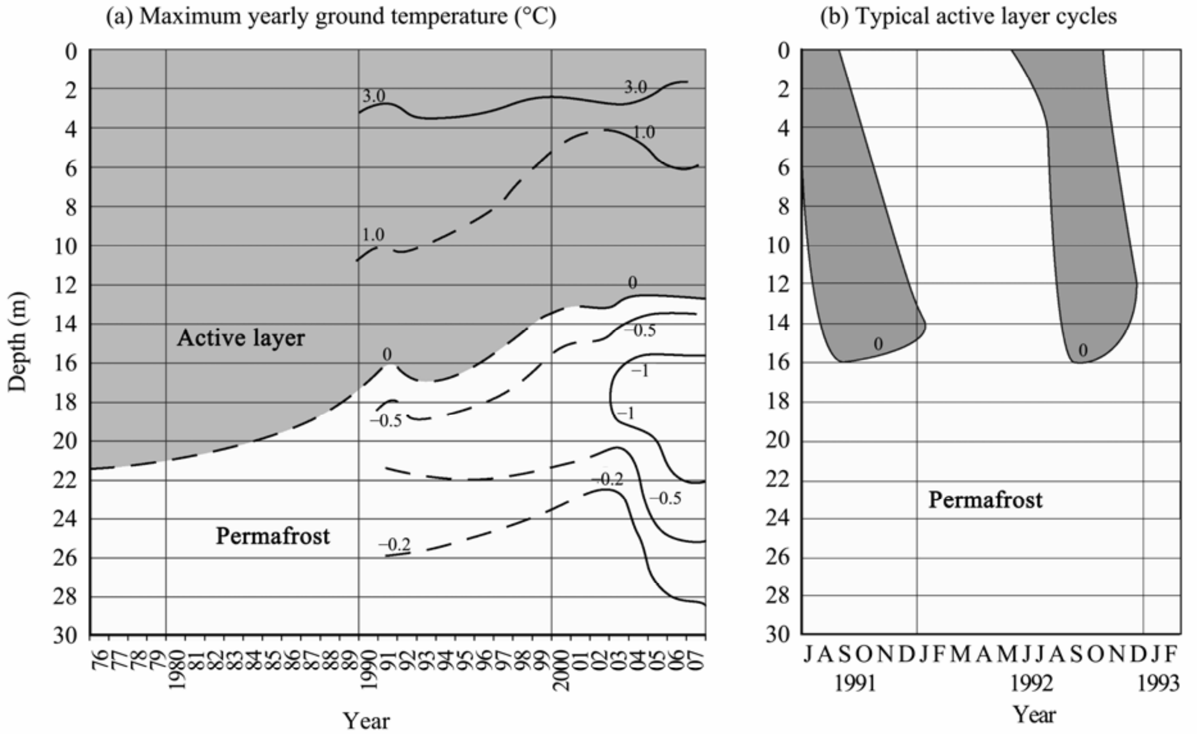


Figure 3 Changes in maximum ground temperature and depth of the active layer as measured on a yearly basis (a), and on a daily basis (b).

The cooling of the MAAT and the lower snow cover south of Calgary have resulted in cooling of the ground, so that the active layer at PM#6 has decreased from c.21 m in 1975 to c.13 m in 2007 (Figure 3). The temperature of the permafrost at 20 m depth has also dropped to below −1 °C. In contrast, the relic permafrost in the ice cave has continued to degrade, so that now ice only remains in the two side galleries (Harris, 1979).

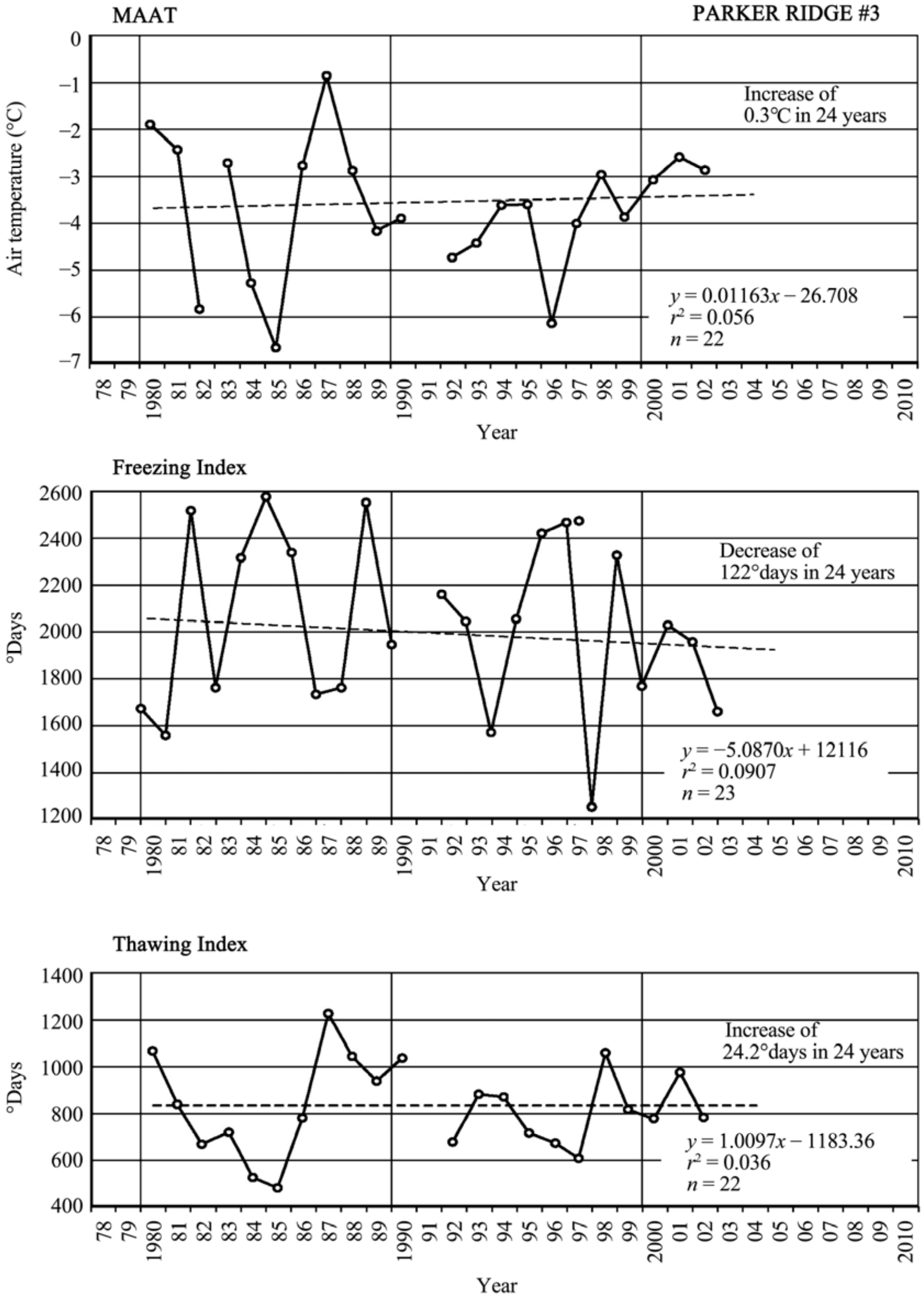


Figure 4 MAAT, STI, and SFI for the weather station at Parker Ridge #3 from 1980 to 2003 inclusive.

At Parker Ridge #3 (52°10.975′N, 117°6.564′W, 2,289 m), the MAAT increased 0.3 °C in 24 years, due to a decrease in the SFI of 122°days versus an increase of the STI of 24.2°days over 24 years (Figure 4). The stations at both Parker Ridge and Plateau Mountain #2 are located in the alpine tundra on mountain tops, but at lower elevations, such as Sunwapta Pass (52°11.465′N, 117°06′W, 2,059 m) there are different results, with an increase in MAAT of 0.88 °C in 28 years with both the SFI and STI decreasing (Figure 5). At both Parker Ridge and Sunwapta Pass, the permafrost appears to be stable, neither aggrading nor degrading.

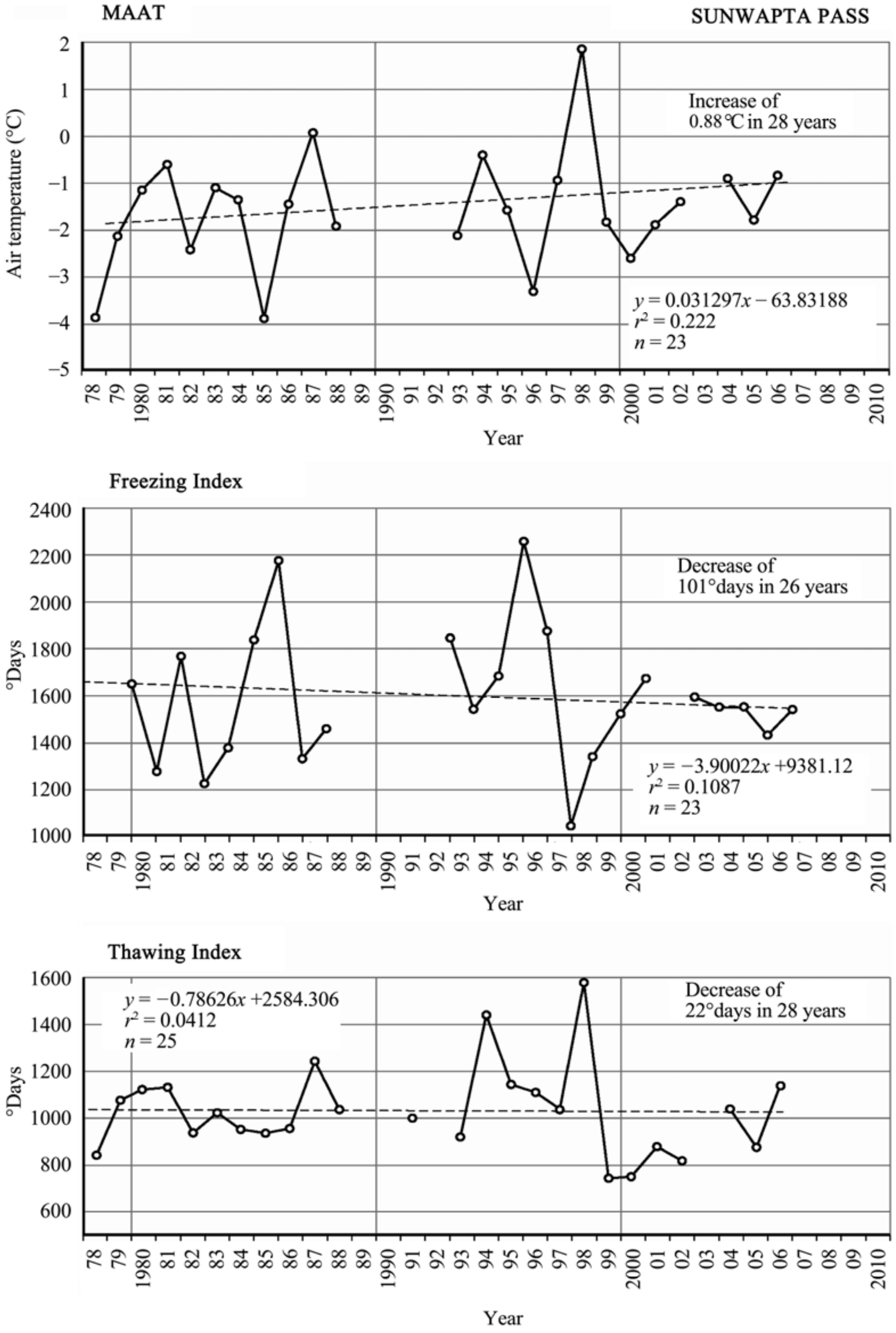


Figure 5 MAAT, STI, and SFI for the weather station at Sunwapta Pass in the subalpine forest for the period from 1978 to 2007.

At Marmot Basin #2 (52°47′36.8″N, 118°6′45.9″W, 2,159 m), again near the crest of the mountain, the MAAT increased 0.6°C in 27 years (Figure 6). In this case, the SFI decreased 761°days while the STI increased 370°days over the 27 years. The only long-term data on snowfall comes from the Middle Chalet at Marmot Basin (Figure 7) and indicates that the snow cover has been decreasing since 1960. Evidence from former avalanche tracks suggests that snowfall was much higher during the last Neoglacial event (Winterbottom, 1974), while data from tree rings at sites where temperature is the limiting factor indicate that increased precipitation must have accounted for the last Neoglacial ice advance (Allen,1982).

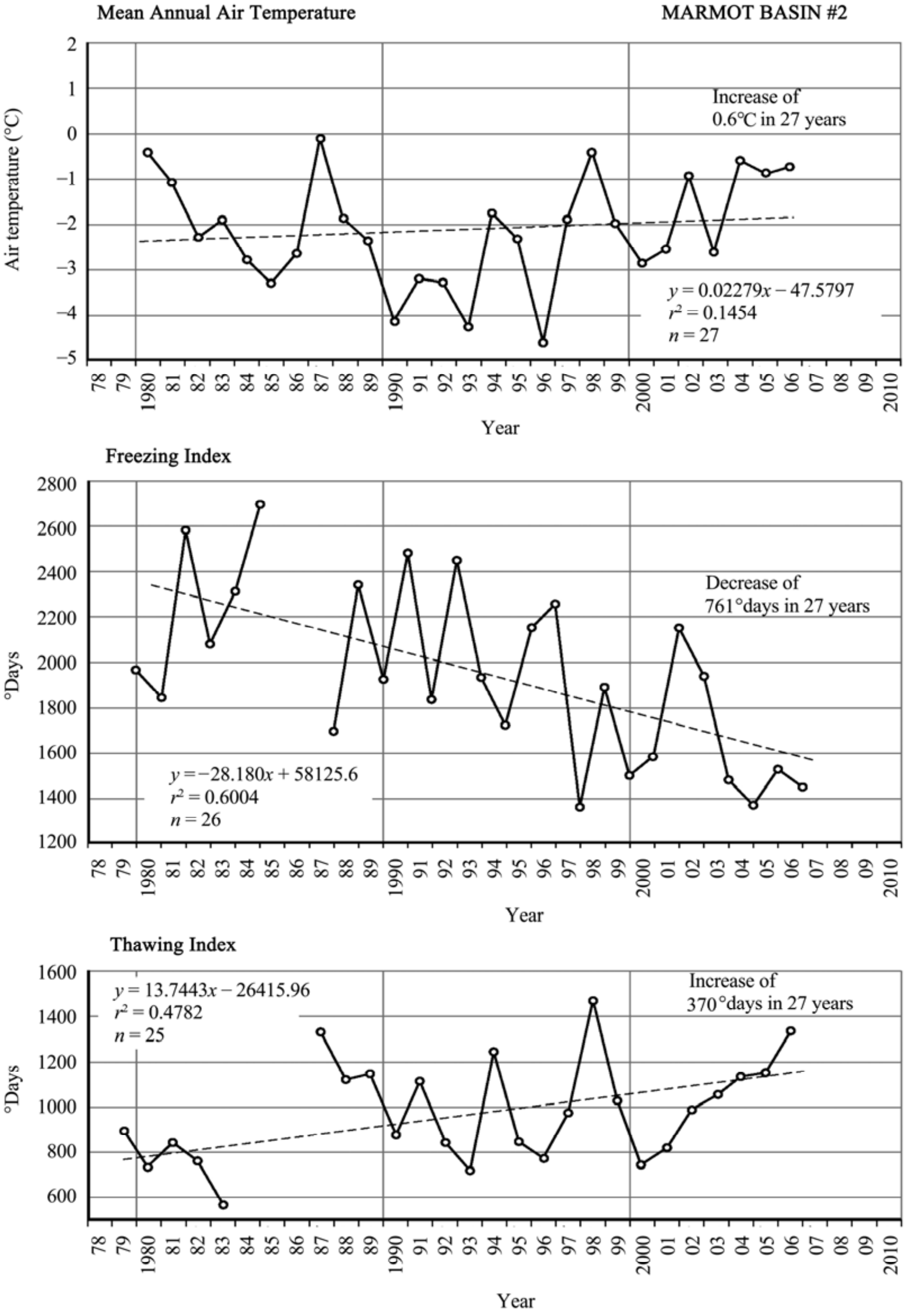


Figure 6 MAAT, STI, and SFI for the weather station at Marmot Basin #2 for the period from 1979 to 2007.

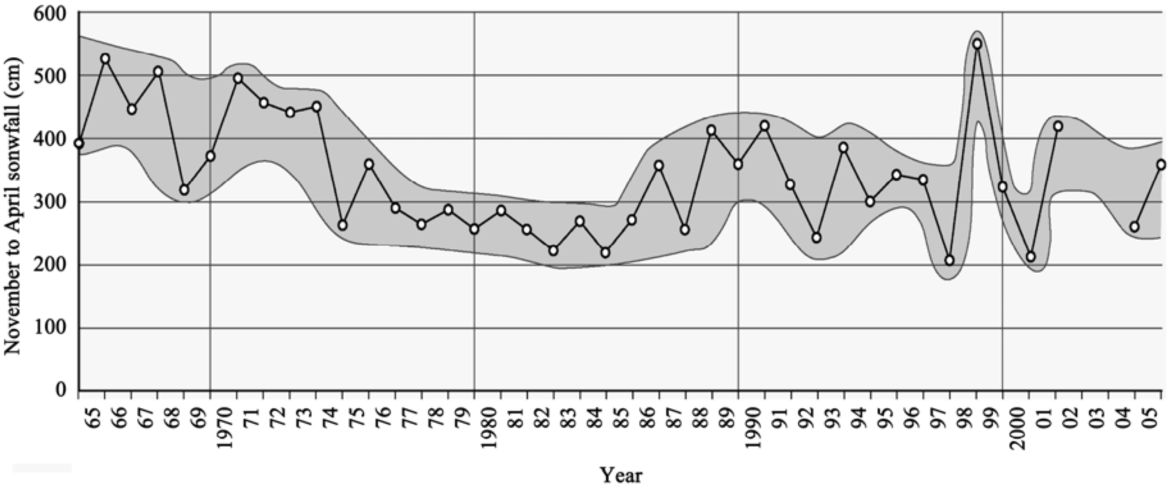


Figure 7 Variation in winter snowfall (November to April inclusive) between 1965 and 2006 as measured at the Middle Chalet at Marmot Basin, just below tree line (data supplied by Marmot Basin Ski Resort).

The thickness of the active layer at Marmot Basin #2 has been shown to be considerably influenced by surface waters percolating through the soil since it lies on the sloping side of Marmot Mountain (Harris, 2002). Marmot Basin #1 lies on the north ridge, and shows little change in thickness of the active layer since studies commenced (Figure 8). This is consistent with only minor warming of MAAT coupled with lower snowfall (Figure 7).

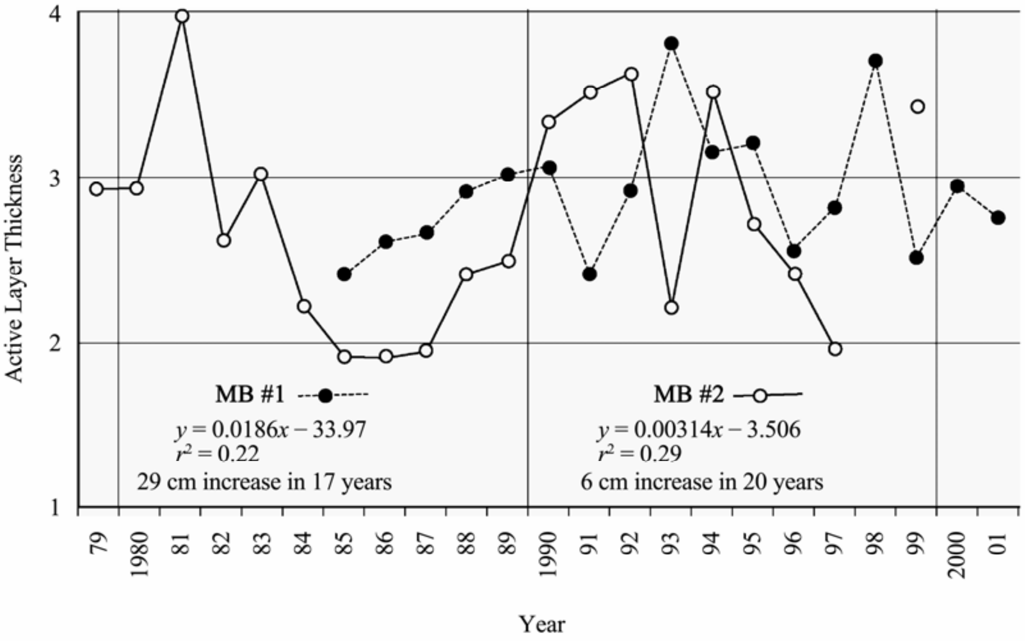


Figure 8 Variation in thickness of the active layer at MB#1 on the ridge crest and MB#2 about 100 m lower on the east-facing slope of Marmot Mountain.

Summit Lake A (58°37′53.7″N, 124°42.183′W, 1,524 m) shows the most extreme changes in MAAT, amounting to a 5.23 °C increase over 14 years from 1982 to 1995, followed by only 0.25 °C during the next 14 years (Figure 9). This was due to a 1,216°days reduction in the SFI and a 631°days increase in STI between 1982 and 1995. Thereafter, the STI became virtually constant but the SFI lost another169°days over the next 15 years.

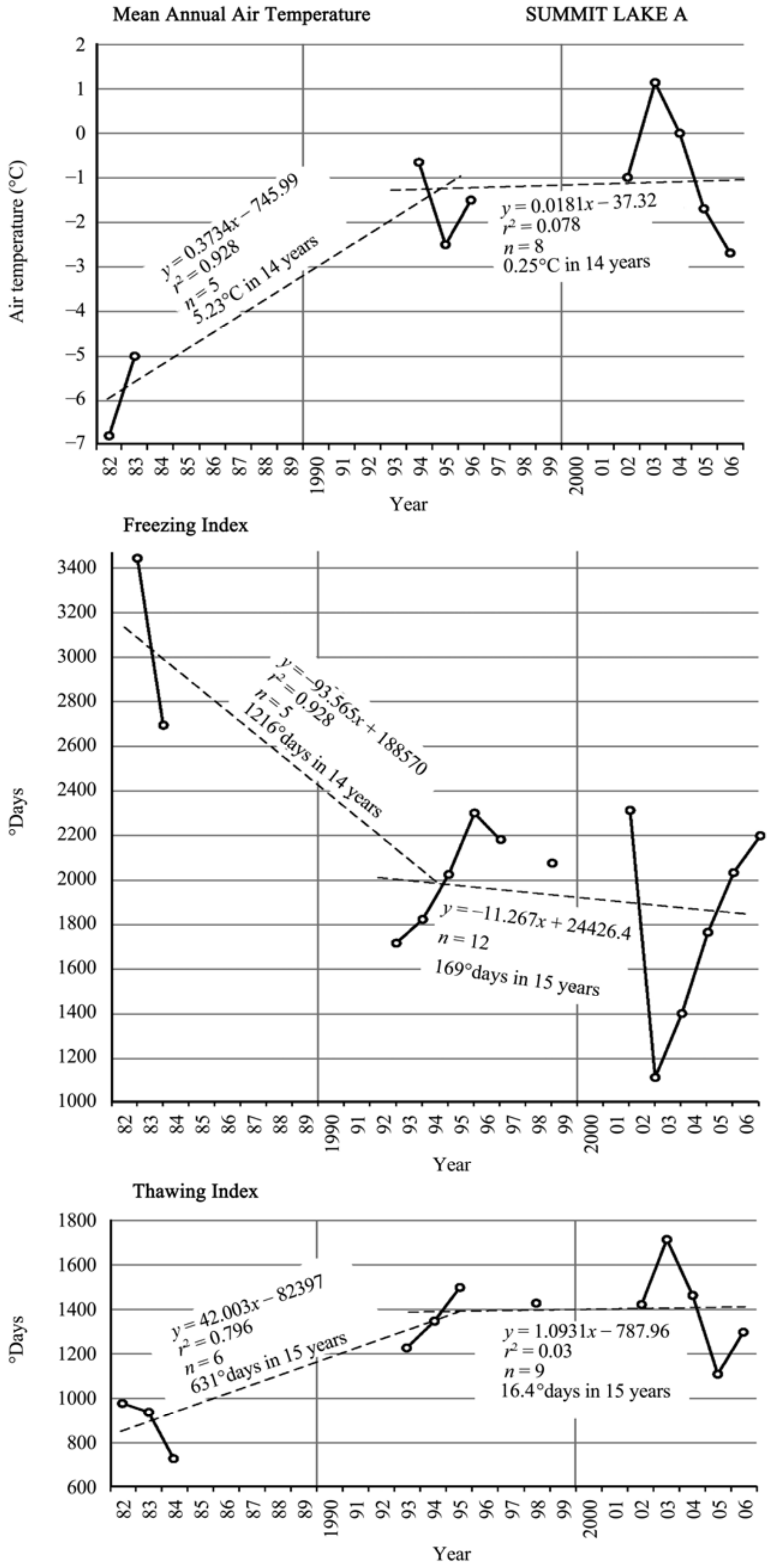


Figure 9 Mean annual air temperature, seasonal freezing index, and seasonal thawing index measured at Summit Lake #A from 1982 to 2006.

Unfortunately, it was not possible to obtain complete data for the years between 1983 and 1994, so the exact shape of the change is unknown. Certainly 1982 and 1983 were very cold years at Watson Lake to the north (Figure 10), but the active layer at Summit Lake, which was about 1.5 m thick in 1983 following refreezing after drilling, became progressively deeper after 1994, exceeding 5 m during the summer of 2006. The nearby slopes are exhibiting spectacular failure with thaw-flow slides developing (Figure 11), indicating that the warming is resulting in considerable melting of ground ice. Further north along the Alaska Highway, the most southerly lithalsas in northern British Columbia (59°44.84′N, 127°20.923′W) are also showing considerable examples of collapse, though they have not been studied in detail. James *et al.* (2008) reported an apparent decrease in permafrost distribution along the southern part of the Alaska Highway based on a re-examination of the presumed sites of the observations by Roger Brown along the Alaska Highway (Brown, 1967b). Unfortunately, the highway has been re-aligned and rebuilt, while the adjoining wetlands have been partly drained, so that the apparent changes they report may also be influenced by other factors besides climate. However, there is little doubt that there has been a substantial change in MAAT rather than the data reflecting merely rather large annual fluctuations.

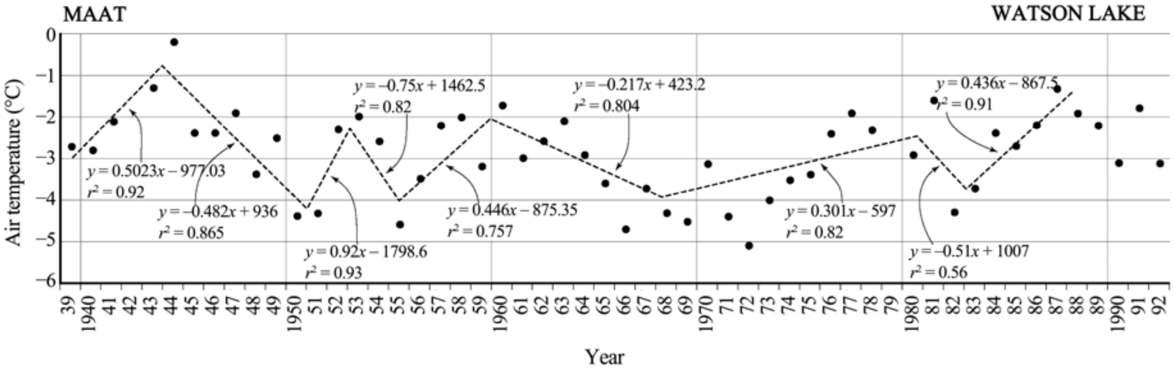


Figure 10 Variation in MAAT at Watson Lake, Yukon Territory, as reported by AES (1993).

The weather station from which data is reported in Figure10 was terminated in 1992, but a new automatic station is now in operation. The regression lines on Figure 10 represent the best fit with the best correlation coefficients to pick out the fluctuations. Note that the record indicates a gentle increase in MAAT between 1970 and 1993, but the long-term record suggests that the variations lie between −1 °C and −5 °C since 1944, *i.e.*, there has been overall stability during this period. The warming at the end of the last Neoglacial event ended in 1942–1944 in the southern Yukon Territory. One difference between the Whitehorse climate data and that from Watson Lake is that there has been a moderate elevation of about 2 °C in the MAAT at Whitehorse since 1970, stabilizing at the new level in about 1985 (James *et al.*, 2008). This is probably the northern fringe of the belt of warming that occurred at Summit Lake.

The data from the rest of the south-central Yukon are quite different from the results obtained from northern British Columbia (Figures 10 and 12), the MAAT having decreased 0.03 °C in 15 years at Fox Lake (61°9.71′N, 135°23′W, 804 m). Both the STI and the SFI also decreased. All the Yukon stations are in valleys, though the local relief is subdued. To the east at Tuchitua (61°19′N, 129°36.337′W, 907 m), the data for the last 14 years show an increase in MAAT of 0.81 °C with both the SFI and STI increasing (Figure 13). A less complete record from Sheldon Lake (62°38.055′N, 131°13.466′W) shows a similar pattern for STI and MAAT, but the SFI appears to be decreasing (Figure 14).

The permafrost at the sites in the Yukon represents a more complicated problem. During the Yukon Field Trip after the Yellowknife Conference of the International Permafrost Conference in 1998, the degrading of the lithalsas at Fox Lake was apparently represented to the visitors as being the result of global warming. However this is inconsistent with the climate data from Fox Lake. The collapse of the market for beaver pelts in the 1980s had resulted in cessation of trapping, and the beaver population boomed. The beavers built dams across the outlet stream, which raised the water level in Fox Lake. This resulted in thawing of the warmer lithalsas in the beaver ponds, with only the coldest lithalsas still surviving. Away from the elevated water levels, the lithalsas are still stable. Lewkowicz (2003) has reported a similar result of beaver activity at Wolf Creek east of Whitehorse.

Twenty-two lithalsa fields have been identified between Marsh Lake in the southern Yukon Territory and Tok in Alaska, including those described by Lewkowicz (2003). Eighteen of these appear to be stable. Fox Lake and Wolf Creek have been discussed above. One of the other two was destroyed during road building and the other along the north shore of Marsh Lake was being seriously damaged by elevated water levels during the summer of 2007 due to mismanagement of water levels by the Hydroelectric Company. The palsas and peat plateaus further north and west are generally intact with a good forest cover on top.

(a)

(b)

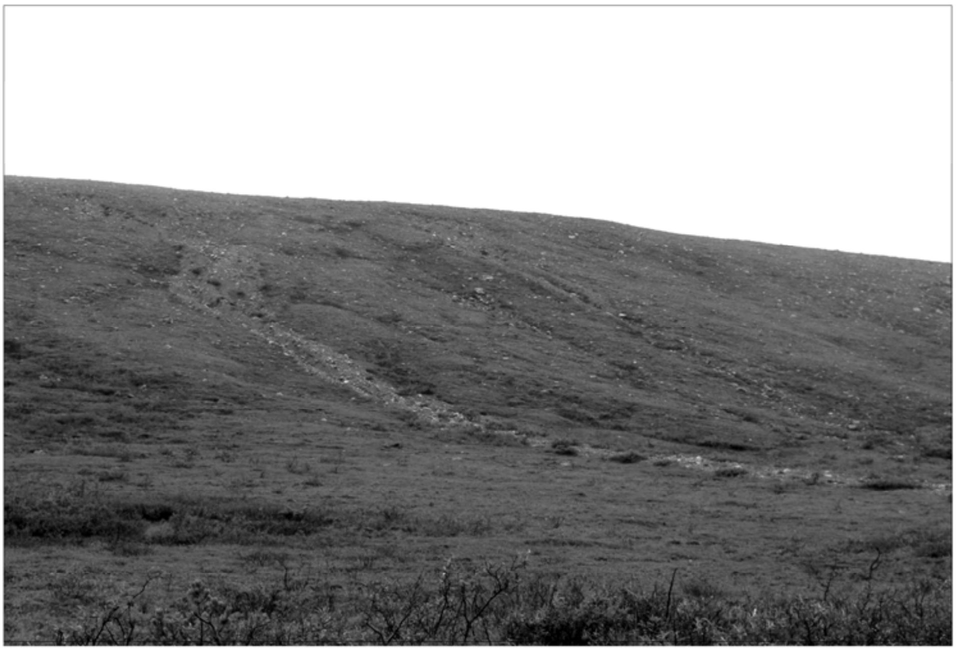
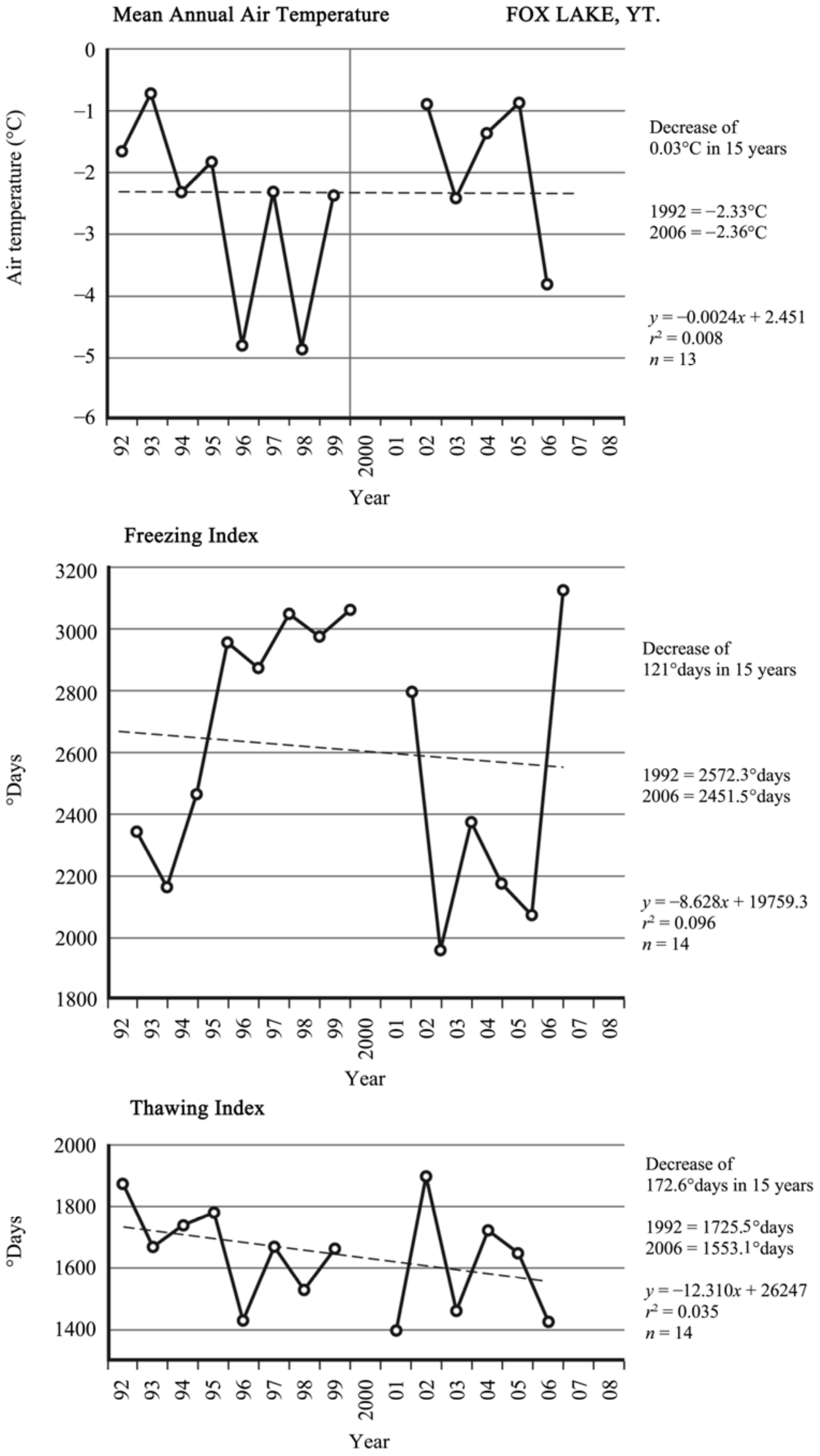


Figure 11 Degrading slope on the alpine tundra just east of Summit Lake #A in August, 2007. (a) Lower slopes and (b) slopes above the borehole.



Mean Annual Air Temperature FOX LAKE, YT.

Decrease of 0.03°C in 15 years

1992 = −2.33°C
2006 = −2.36°C

$y = -0.0024x + 2.451$
$r^2 = 0.008$
$n = 13$

Freezing Index

Decrease of 121°days in 15 years

1992 = 2572.3°days
2006 = 2451.5°days

$y = -8.628x + 19759.3$
$r^2 = 0.096$
$n = 14$

Thawing Index

Decrease of 172.6°days in 15 years

1992 = 1725.5°days
2006 = 1553.1°days

$y = -12.310x + 26247$
$r^2 = 0.035$
$n = 14$

Figure 12 MAAT, STI, and SFI for Fox Lake, Yukon Territory for the period from 1992 to 2007.

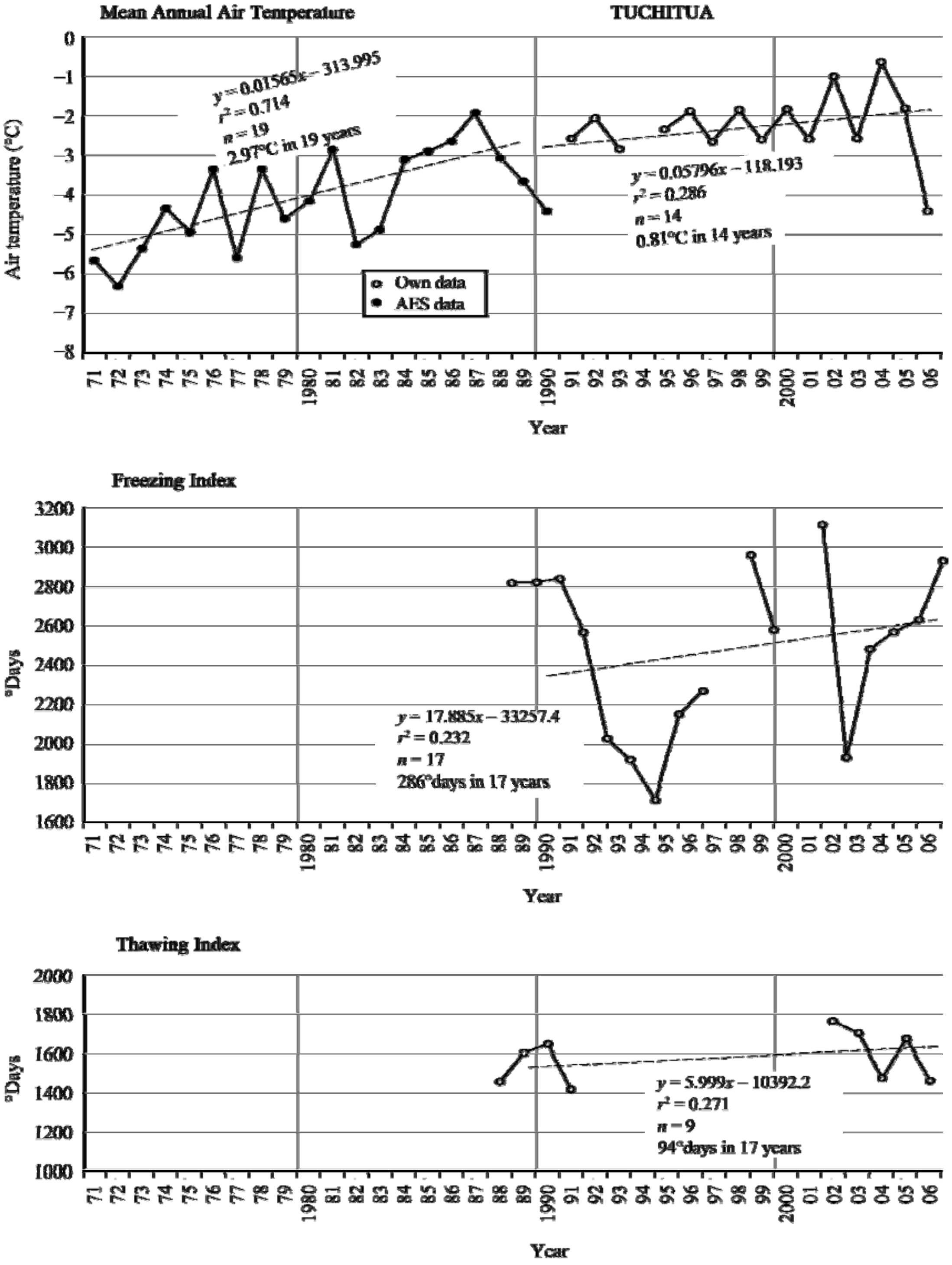


Figure 13 MAAT, STI , and SFI measured at Tuchitua from 1991 to 2006, together with the MAAT from data published by AES (2002) for 1971 to 1990.

At Tuchitua, the grounded peat plateau at Km-161.7 along the Robert Campbell Highway was close to collapse in 1992 (Harris and Schmidt, 1994) when the Yukon Highway Department put in a new culvert about 30 cm lower than it was previously. There is rejuvenation of the peat plateau with cooling of the core (Figure 14).

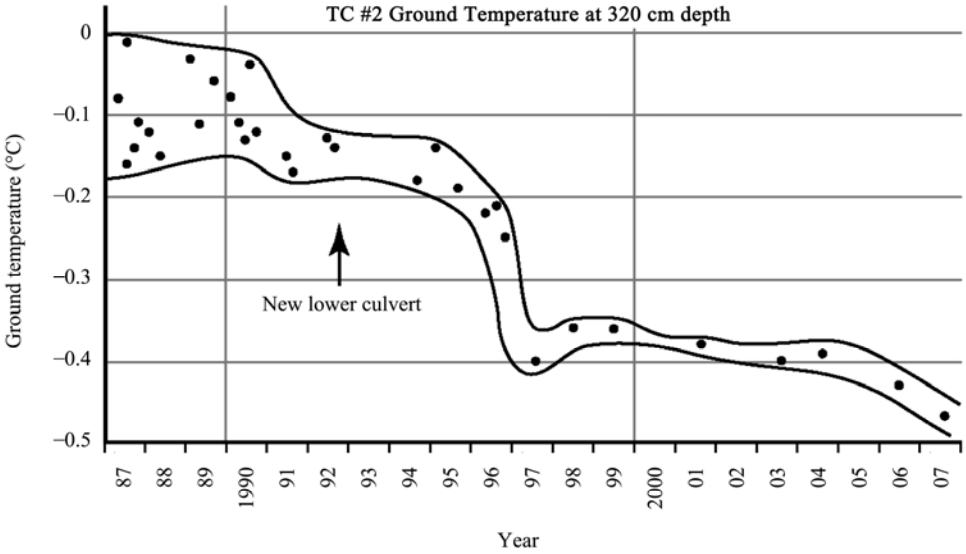


Figure 14 Changes in ground temperature at 320 cm depth at TC#2 in the peat plateau at Km-161.7, Robert Campbell Highway from 1987 to 2007.

Kershaw (2003) has provided convincing evidence for the degradation of permafrost on the upper slopes of the Mackenzie valley, east of the continental divide between the Northwest Territories and Yukon Territory. He also claimed a similar degradation was occurring on the west side based on recent degradation of two floating palsas. Unfortunately, degradation of floating palsas can be caused by a decrease in volume of the surrounding water body, even if the MAAT remains constant. A decrease in the water level occurred at the embryonic palsa described by Harris and Nyrose (1992) as a result of destruction of the moss dam in 1992, and resulted in the degradation of the palsa. The water body in which it floated decreased in volume so that the water increased in temperature during the summer, thus thawing the core of the palsa. The dew pond containing the floating palsa in the MacMillan Pass also shows evidence of a decrease in water level.

A better check on permafrost stability in the valley at MacMillan Pass is provided by two palsa fields two kilometers further west along the MacMillan River floodplain. Figure 15 shows that these appeared very stable during the summer of 2007.

In addition, measurements of ground temperature in a borehole in a stable peat mound, 1 km east of the airport runway, show negligible changes in the ranges of the readings since 1951. It therefore appears that there is a climatic divide along the border between the Yukon Territory and the Northwest Territories.

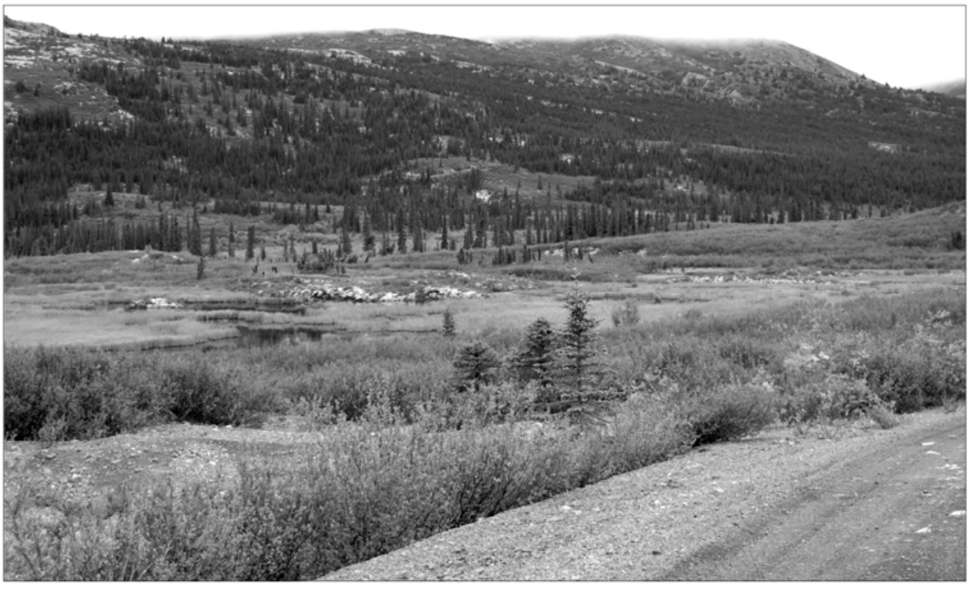


Figure 15 An apparently stable palsa field on the floodplain of the MacMillan River in 2007.

5. Discussion

5.1. The pattern of regional climatic change

Figure 16 shows the regional pattern of climate change since 1980 based on the published government climate data and the present study. Harris (2006; 2007) examined the long term data sets for 17 Class A weather stations operated by the National Weather Service in Alaska together with data from eight stations in the Yukon Territory published by the Atmospheric Environment Service (AES, 1993), and found that there was substantial variation in the pattern of change in MAAT since 1950. Along the Arctic coast of Alaska, the Mackenzie valley, and in the Summit Lake area, there is evidence of substantial, rapid warming. In Central and Southern Yukon and Alaska and south of 52°30′N in the Cordillera, there is no change. South of 51°N and south of Dawson City, there is cooling.

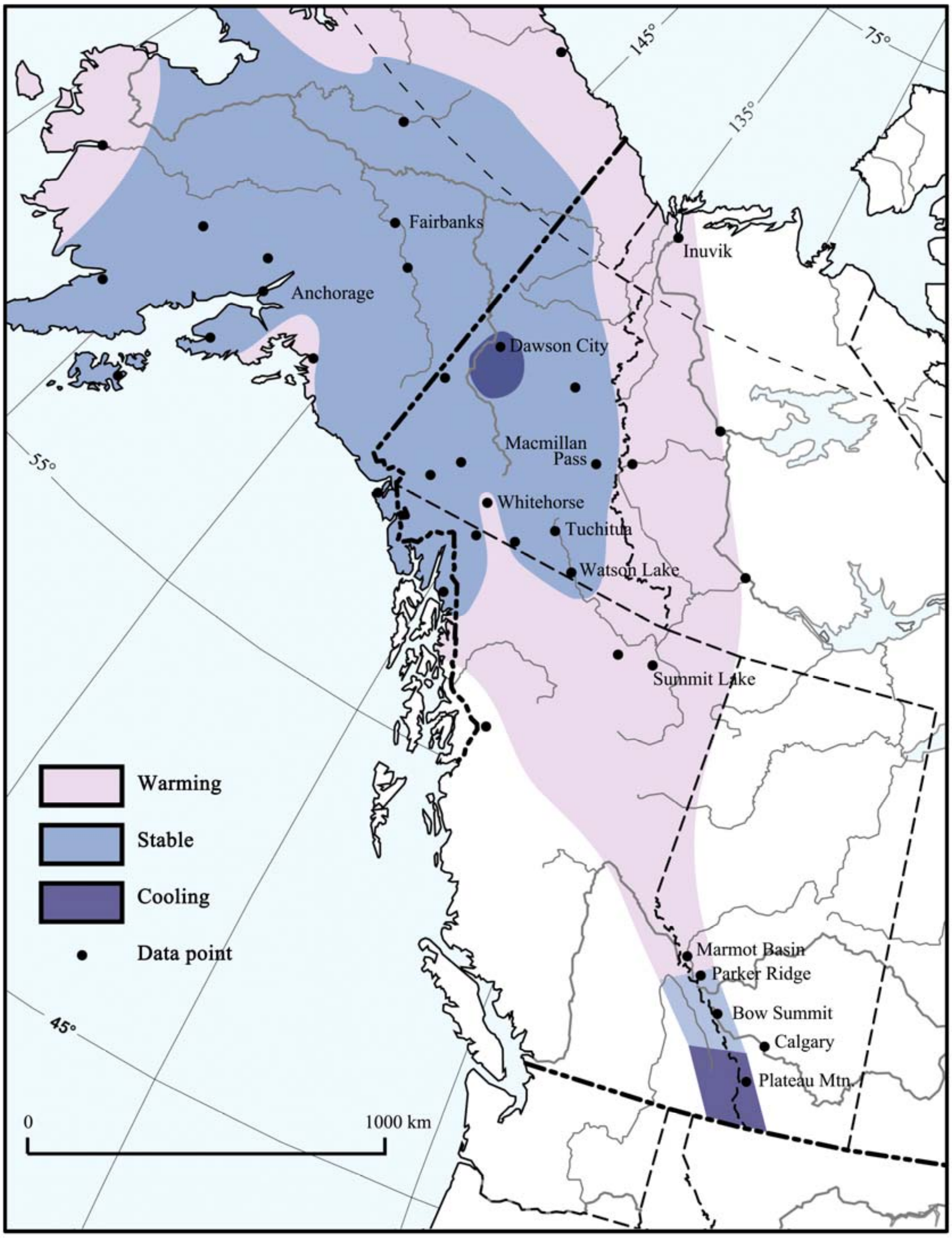


Figure 16 The apparent regional pattern of temperature changes from 1970 to 2006 (partly after Harris, 2006; 2007; 2008).

5.2. Causes of the results

What is rarely discussed when considering climate change is the fact that to maintain the MAAT in the higher latitudes of the Northern Hemisphere, 30 percent of the heat absorbed by the surface of the Earth in the tropics must be transported northwards. Absent this transport, the MAAT in the higher latitudes would be similar to that in Antarctica. The three main agents involved in the transport are ocean currents, thermohaline circulations and movement of air masses. In the case of the latter, the air occupies a zone where it is free to move according to regional changes in air pressure.

The ocean currents and thermohaline circulations transport tremendous quantities of heat towards the north using both the north Pacific and north Atlantic oceans. A slight change in the trajectory of the current can cause cooling in one area and warming in another. In the case of the last change in the Pacific Interdecadal Climate Oscillation (Mantua *et al*., 1997) in 1975, there was an abrupt 2 °C increase in temperature along the coast of British Columbia and Alaska, with the effects penetrating across Alaska west of the Wrangell-St. Elias Range (6,000 m high). The 6,000 m high mountains appear to have protected eastern Alaska and the Yukon Territory from the changes (Figure 17). This change is equivalent to 100 years of climate change predicted by CO_2 models, and took place in a mere two years.

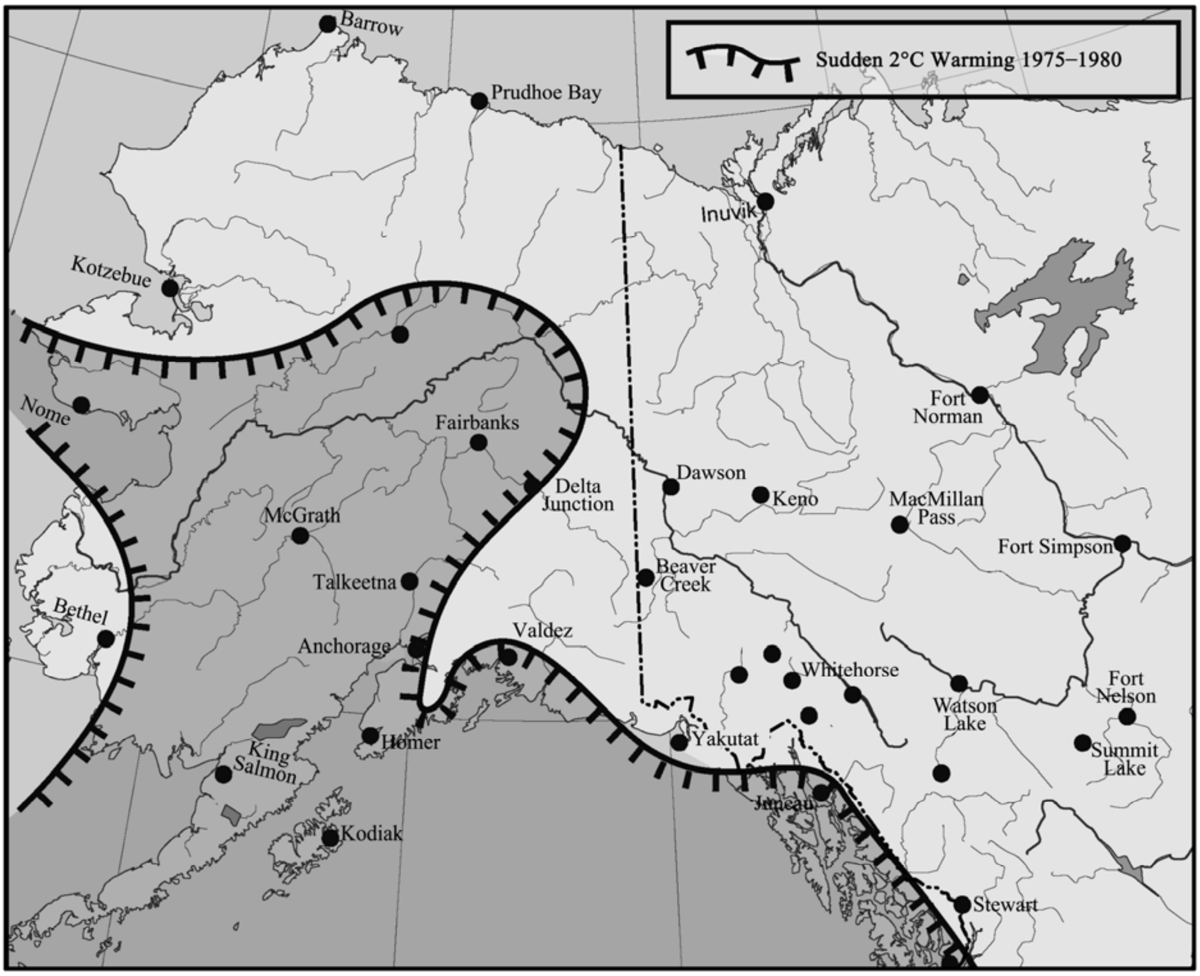


Figure 17 Area of Alaska affected by the 2 °C warming in MAAT in 1975 (after Harris, 2007).

The third method of transport of heat towards the North Pole is by the movement of air masses. There is a major source area of cT air in summer coming north from the deserts of southeastern California, Nevada, and Arizona between the eastern and western Cordilleras (Figure 18). The coastal ranges along the Pacific Coast are high enough to prevent the changes in MAAT along the Pacific coast from affecting the interior of the mountains. The maritime air must pass over the Cascade Mountains of the Pacific coast. These are at least 1,400 m at their lowest point and rise as high as 6,000 m in the Wrangell-St. Elias Range of the south coast of Alaska. Figure 17 shows that the Wrangell-St. Elias massif effectively blocked off the effects of the 2 °C warming from eastern Alaska and the Yukon Territory. Further south (Figure 18), the maritime polar air becomes modified as it crosses the Cascade Range, which forms a continuous barrier over which the air mass must climb. There is heavy precipitation and cooling during its ascent over the mountains, with warming and drying as the air masses descend into the interior valleys. The characteristics of the coastal air are masked by the modifications, and the resulting warm, dry air joins the cT air moving northwards in summer or moves north and east along the Cordillera, finally escaping eastwards through one of the lower parts of the Eastern Cordillera (Figure 19), to continue eastward across the prairies under the influence of the rotation of the Earth and the Coriolis Force. Earlier, Axelrod (1950) had demonstrated that there was a change from Subtropical Forest to Steppe-Grasslands in the interior of Washington State during the middle of the Tertiary period, signaling the rise of the western wall of mountains of the Cascade Range and the desertification of the area to the east.

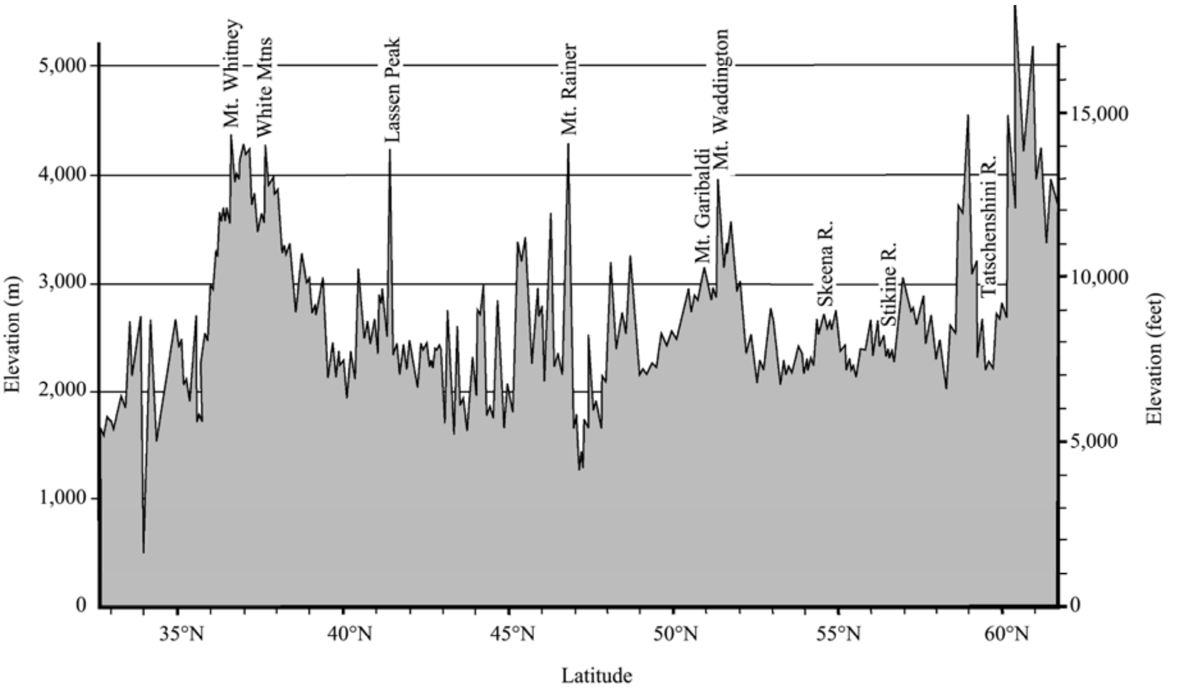


Figure 18 The wall formed by the Cascade, Coastal and Wrangell-St. Elias mountains that the westerly air masses must surmount to reach the interior of the Cordillera.

The general atmospheric circulation along the length of the middle of the Cordillera in the northern hemisphere is shown in Figure 20. Hot air from the deserts of California, Arizona, and Nevada moves north in summer, hemmed in by the coast mountains in the west and the eastern Cordillera to in the east (Figure 21). At the junction of the cT air and the cP air is the polar jet stream.

The Eastern Cordillera makes the escape of the warm air moving north along the central plateau difficult until it reaches the headwaters of the Missouri River, which provides a break in the mountain front in northern Montana (Figure 21). Additional breaks in the mountains occur at the Crowsnest Pass, the Kicking Horse Pass and the Yellowhead Pass at Jasper. The next low place to the north is at the Peace River, followed by the Summit Lake area and finally the Liard River to the north in northern British Columbia. Under the conditions pertaining 40 years ago, the bulk of the air swung eastwards, mainly escaping on to the prairies through the Missouri, Crowsnest, and Kicking Horse Passes. This maintained the steppe conditions of the northern apex of the Palliser Triangle. The fact that the SFI has been decreasing during the last thirty years at virtually all the weather stations in the study area indicates a weakening in the Arctic air masses, permitting the combined cT and mP air masses to travel further north to the gaps in the Eastern Cordillera at Jasper, the Peace River, and the lower mountains west of Fort Nelson. This brings increased STI values to the Jasper-Fort Nelson area but reduced STI south of Jasper. Some of this warm air even penetrates southern Yukon as far as Whitehorse in the lea of the St Elias Range. This pattern matches that postulated by Nkemdirin and Budikova (2001).

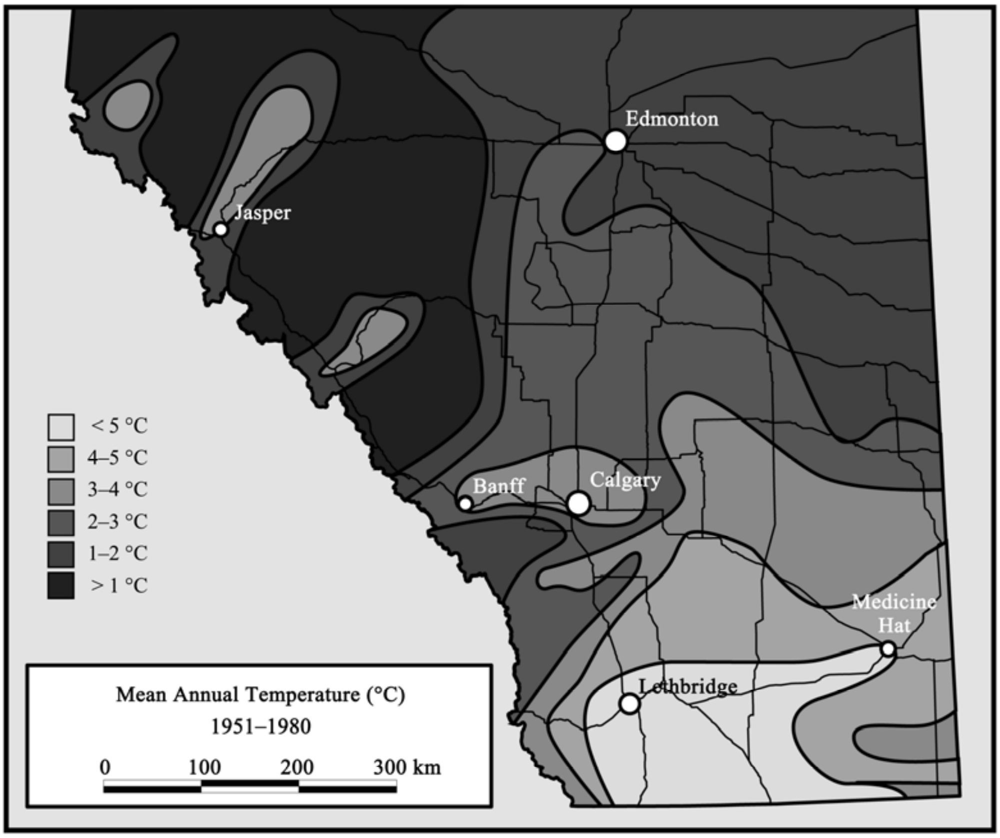


Figure 19 Average mean annual air temperature measured by the Atmospheric Environment Service at stations in Southern Alberta between 1951 and 1980 (AES, 2002). Although the Chinook winds occur mainly in the Lethbridge area, the warming due to westerly winds coming out of the larger mountain valleys is obvious along the entire mountain front.

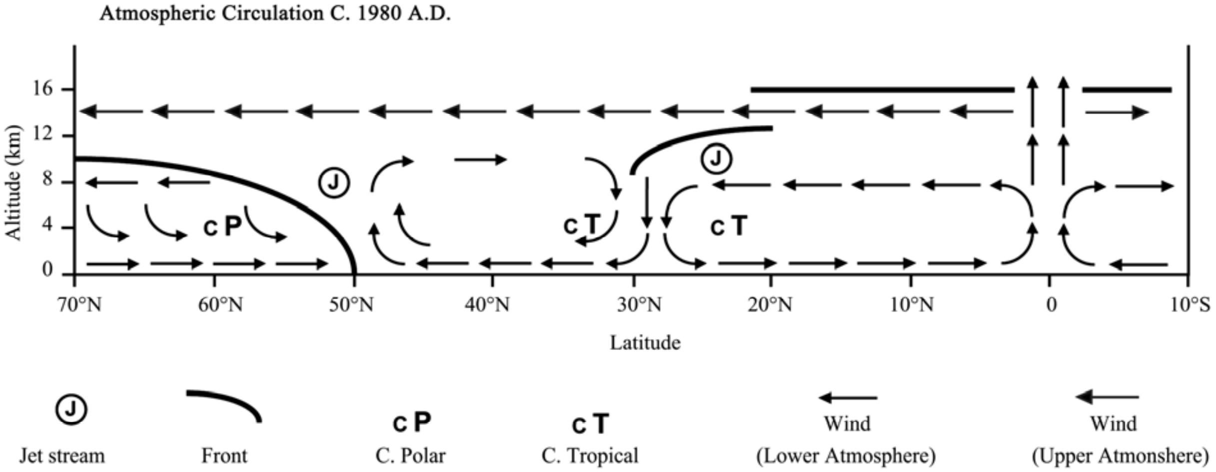


Figure 20 Major south to north air circulation along the middle of the Western Cordillera of the Americas in 1980.

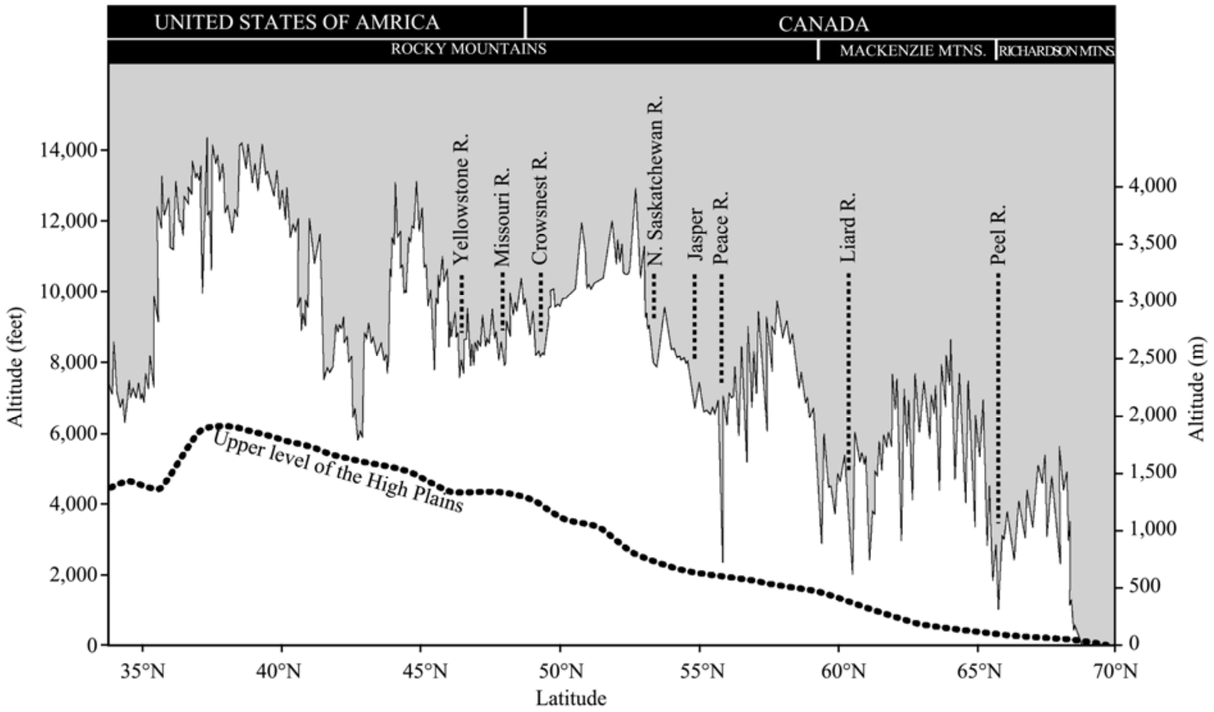


Figure 21 The profile of the crest of the Eastern Cordillera from New Mexico, north to Inuvik. Note the limited number of river gaps where air can readily move eastwards from the interior plateau.

The reduction in the depth and size of the winter cP and cA air coming south from Yukon and Alaska results in these air masses following a trajectory towards Winnipeg, but they only back up against the mountains in the south if the cold air mass is deep enough (see Figure 22). For the period of study, it has decreased in size and depth, resulting in a decrease in SFI. This change resulted in the mean northern jet stream position advancing northwards between 1982 and 1995, resulting in a pronounced increase in the STI and MAAT in the area west of Fort Nelson. Southern Alberta was spared some of the advection heating from the cT air mass and therefore has a lower STI and MAAT.

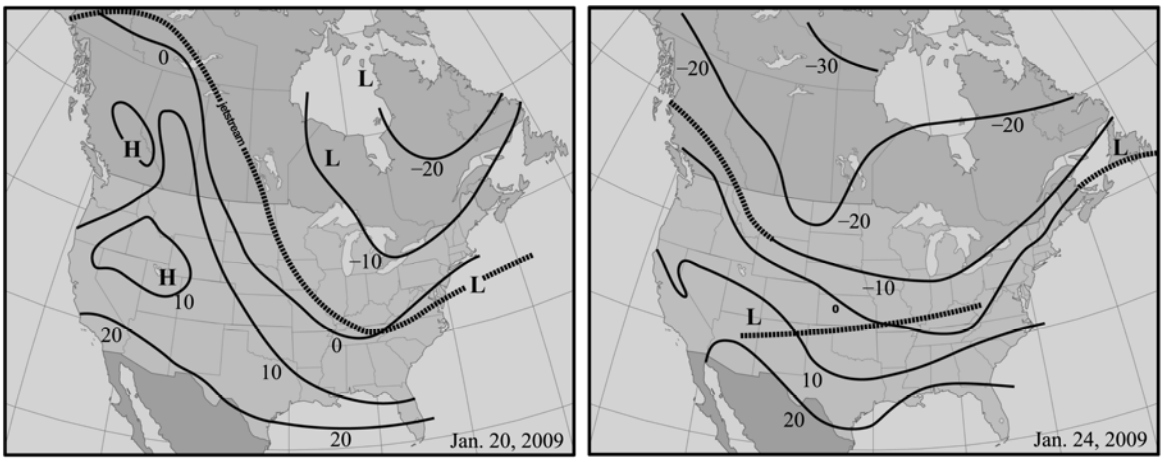


Figure 22 Synoptic charts for winter weather patterns (January 20th, 2009 and January 24th, 2009).

This illustrates the fact that climate changes do not have the same effect across the world as suggested by the term "global warming". Instead there are significant variations from one region to another that cannot readily be predicted in our present state of knowledge. The enhanced warming along the Arctic coast is probably partly due to the change from snow cover (reflecting 85 percent of the incoming radiation) to bare soil (absorbing c. 75 percent of the radiation) or to water, which being translucent, absorbs five to seven times the incoming radiation of soil (Pavlov, 1999; Harris, 2002). The air takes its temperature from the source area, modified by the temperature of the surface it passes over, hence the warming. Hinkel *et al.* (2003) have also provided evidence of a heat island effect at Barrow, Alaska, which may account for at least part of the increase at that site (see also Klene, 2007). Klene (2007) also questions the effects of changes in instrumentation, station moves and changes in times of observations.

The marked warming in the Summit Lake area is the result of the change in position of the jet stream as explained above, but this warm air also heats the area around Great Slave Lake, warming the Mackenzie River water before it moves north along the Mackenzie valley. How important this is in explaining the increased MAAT along the river remains to be determined.

The lack of change in the mountain valleys of central and southern Yukon and Alaska has been shown to be a result of the combined effects of cold air drainage, inversions and steam fog (Harris, 2006; 2007). If the regional air warms up and the warm air overrides the cold air trapped in the mountain valleys, a thicker cloud layer develops at the inversion, thus producing decreased insolation at the ground. The cold air drainage requires a certain minimum temperature to be exceeded at a given site for it to occur (Figure 23). Since a 2 °C warming does not appreciably alter the period in winter when it is colder than this threshold, cold air drainage remains a major factor maintaining permafrost stability. Finally, most mountain valleys have extensive lakes and fens.

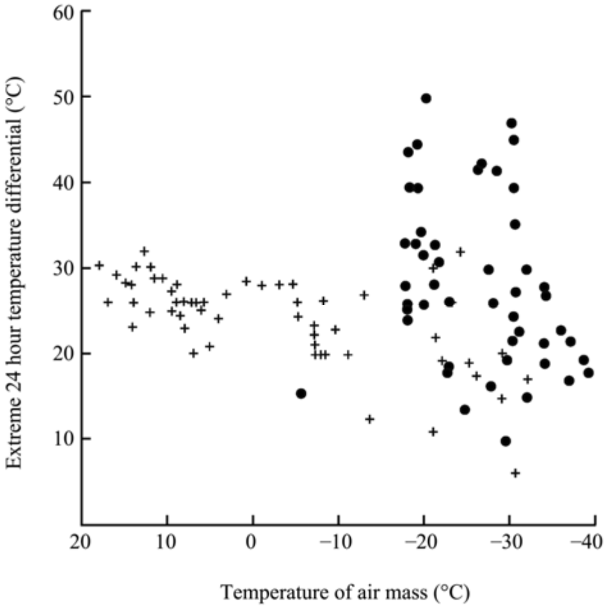


Figure 23 The temperature of the still cP air mass plotted against presence or absence of cold air drainage at Fox Lake, Yukon Territory for the winters of 1987–1996 (modified from Harris, 2007).

When colder air overlies the open water in the early fall, steam fog develops, cutting down on the insolation reaching the ground surface until the water becomes frozen in early December (Figure 24). By then the incoming radiation at these northern latitudes is minimal. These three processes cannot occur on the sloping sides of the mountains, hence the climatic divides.

The discussion above explains the mechanics of the changes, but does not explain the causes. Presumably any transport of additional heat into the Arctic Basin could result in a weakening of the polar air masses. Sheridan (2003) has suggested that the Pacific North American Pattern indices (PNA) are a cause and part of the mechanism. This theory assumes that the mid-troposphere high pressure centers over Hawaii and Alberta and low pressure centers over the Aleutians and Florida drive the system. With a positive PNA, the mid-troposphere highs and deep lows result in weaker cP / cA air masses, which then move east to give eastern North America a cold winter while the mountains of western North America enjoy a warmer winter. In any case, there has to be a well-developed high in the troposphere above Alberta to produce the return flow to the deserts in the southern United States (Figure 20).

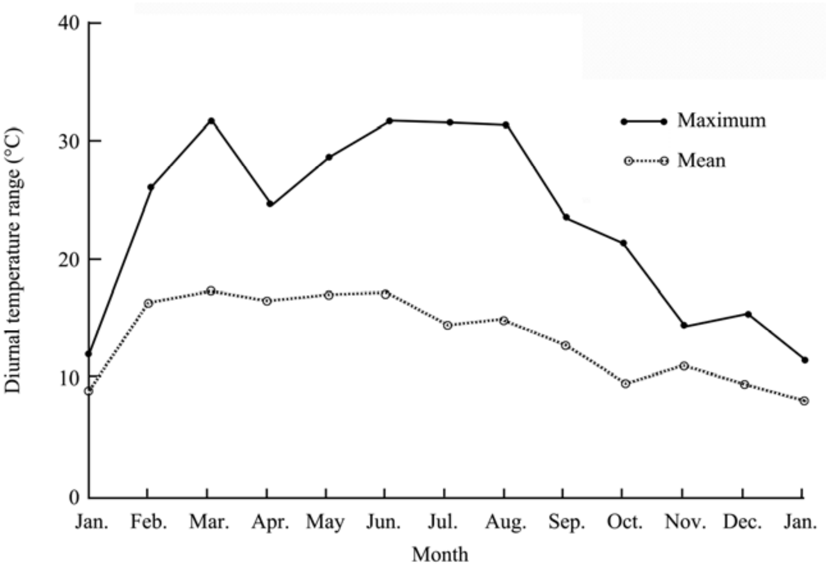


Figure 24 Comparison of the average mean monthly diurnal air temperature range with the average maximum temperature range at Fox Lake, for 1987–1996 inclusive (modified from Harris, 2007).

5.3. Importance of these results

In actual practice, the primary function of the Atmospheric Environment Service in Canada is to provide reasonably accurate weather forecasts for the public. To this end, its weather stations are located in areas where people live. Accordingly, if one needs climate data for sites away from such areas, *e.g.*, the upper slopes of mountains, it is necessary to establish and run independent stations as has been done in this case. If these are located strategically so as to monitor any changes in the prevailing air masses and climate of the region, they can provide a unique data base that cannot be obtained in any other way. Thus the data obtained in this study augments the AES and U.S. National Climatic data from stations in subarctic areas such as the Yukon Territory and Alaska.

The fact that the response to climate changes varies from area to area suggests that some areas present far fewer problems for engineering projects such as pipelines than others. It was fortunate that the trans-Alaska pipeline left the North Slope by the shortest route and then crossed relatively stable areas of permafrost before reaching areas lacking permafrost near Valdez. Building a pipeline along the Mackenzie Valley is likely to face far more maintenance costs due to the gradual warming of the ground in that area.

Examination of past estimates of changes in climate by experts on the climates during the major glaciations of the Pleistocene and Pliocene indicates that some areas only changed MAAT by about 8 °C while the change exceeded 18 °C elsewhere (Washburn, 1979; Isarin, 1997). All areas changed their MAAT during the extreme climate changes occurring during major glaciations, but it seems likely that continental mountain climates in areas with deep valleys may exhibit much lower variations (Harris, 2007). This may explain the abundant fauna and flora in parts of Beringia during these cold events, since it may have represented a relatively warm refugium at that time.

The data obtained during this study also act as a source of factual data for biogeographers and ecologists. Without it, they must rely on models based on various assumptions such as those predicting widespread "global warming". It is clear that these models badly need checking against factual data of the kind produced during the present study, if they are to be improved.

6. Conclusions

Thirty years of climate data from a north-south transect along the Eastern Cordillera in western Canada indicates that any climate changes are rather local instead of global (Figure 17). Warming has occurred between Jasper and the 60° parallel, climaxing at Summit Lake, west of Fort Nelson. The southern and central Yukon exhibit a relatively stable climate while the Arctic Coastal slope and the Mackenzie River valley are warming. The area around Calgary has had a stable climate while the mountains to the south are cooling, as is the area south of Dawson City. These changes appear to be the result of weakening of the polar air masses and a strengthening of the mid-troposphere Alberta High. This results in a movement northwards of the average position of the northern jet stream which appears not to have been considered adequately in developing the existing models of global climate change.

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