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A climatic variation observed in permafrost temperature at Kangiqsualujjuaq in northern Quebec

Lai Yuanming (赖远明)[1], Wu Ziwang(吴紫汪)[1], Zhu Yuanlin(朱元林)[1] and Michel Allard[2]

1 *State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China*

2 *Northern Study Center, Laval University, Sainte-Foy, Quebec G1K 7P4, Canada*

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Abstract Permafrost temperatures from the surface down to about 9 m from 3 boreholes distributed around Kangiqsualujjuaq village on the coast of Hudson Strait were recorded and analyzed for the period 1989-1998. The results indicate that the permafrost is getting warm along the southern shore of Hudson Strait from 1993 to 1998 though it became cooling for the past 40 a or more. The observed trend in the order of 0.098 ℃/a at the 9 m depth is consistent with the long-term regional warming observed in air temperatures. It also coincides with that all the global circulation models predict an enhanced warming in polar regions associated with the increase in concentration of greenhouse gases in the atmosphere.

Key words climatic variation, permafrost temperature, northern Quebec.

1 Introduction

Although the relationship between permafrost thermal regime and present climate is difficult to assess because of the complex effects of surface factors, such as organic cover, surface humidity, vegetation and snow cover (Lachenbruch *et al*. 1988), a change in air temperature will eventually lead to a shift in ground temperature. One way to use permafrost as an almost direct climate-change indicator is to monitor ground temperatures for several years at sites selected for their geomorphological and ecological stability. That is why scientists in Russia, Canada, the U.S.A and other countries have paid attention to permafrost evolution and/or expected changes in climate. Lunardini(1981) has presented the heat transfer in cold climates. Taylor and Judge(1979) have made studies of permafrost in northern Quebec. Lachenbruch and Marshall (1986) have investigated the climatic change according to the geothermal evidence from permafrost in Alaskan. Zhang and Osterkamp(1993) have discussed changing climate and permafrost temperatures in the Alaskan Arctic. Their results show that a variable but widespread warming (typically 2 ℃ to 4 ℃) occurred at the permafrost surface during the 20th century. After analyzing long-term air temperature records and ground temperature measurements along the southern shore of Hudson Strait, northern Quebec, Allard *et al*. (1992, 1995) found that this area had actually experienced continuous cooling for more than 40 a. People show the increasing concern for climate changes, it is very important to carry out continuous shallow geothermal measurements to gain a better understanding of the actual climate controls over permafrost thermal regime and to monitor the thermal response of permafrost to climate variations at the annual and short-term scales. In order to further study the recent climatic variation along the southern shore of Hudson Strait, Quebec, we have analyzed the data of air temperature and permafrost temperature for past ten years(1989 – 1998) and found that the climate there is getting warm after it had experienced cooling for more than 40 a.

2 Study site

The study site, peat plateaus, near the village of Kangiqsualujjuaq (see Fig. 1) is located in the north of Ungava Peninsula, in Nunavik of northern Quebec(65° 57′ W, 58°40′ N), within the zone of discontinuous permafrost(Seguin and Allard 1984). The valley bottom emerged from the D' lberville sea and was occupied by a lake at least some 5400 a B. P.. A peat bog started to develop and invaded the lake some 4500 – 4300 a age. The permafrost growth close to the present lake, in the center of the valley, occurred at about 1800 – 1600 a B. P.; frost heaving in the periphery of the present peat plateau took place somewhat later, about 800 a B. P..

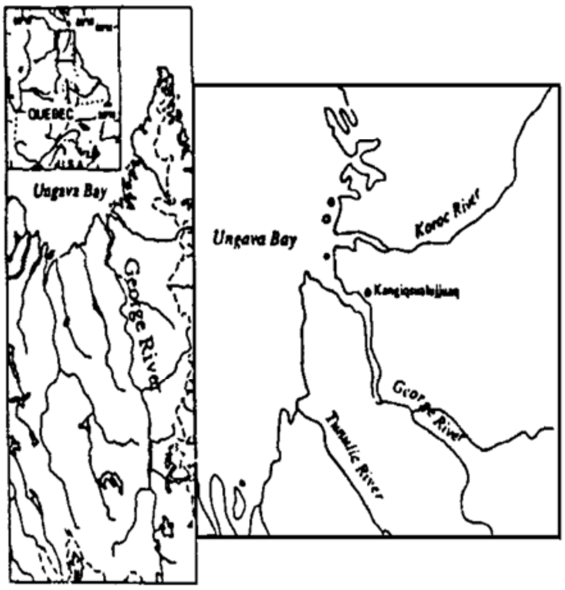

Fig. 1. Location of Kangiqsualujjuaq.

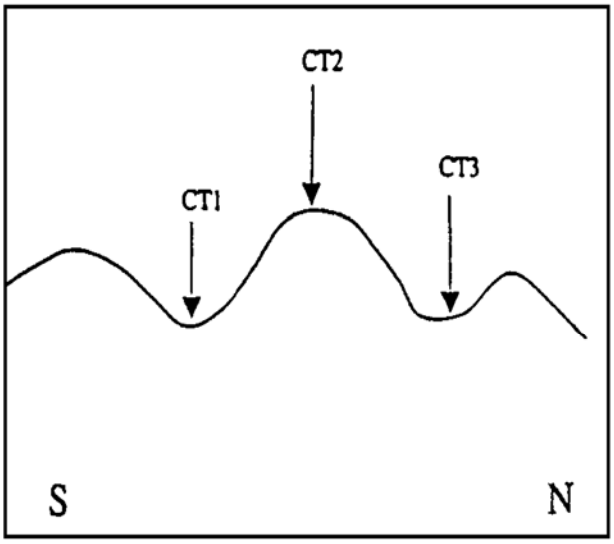

Fig. 2. Locations of CT1, CT2 and CT3.

3 Methodology and instrumentation

Three holes were drilled at this site to a depth of 9 m (CT1, CT2 and CT3, shown in Fig. 2). The borehole sites are at an elevation of 105 m a. s. l.. CT1 and CT3 are in depressions of mounds. CT2 is on top of low hill in order to avoid the interference of snow cover. Due to wind-drifting, the site at CT2 remains almost snow-free all winter. Snow at CT3 can be accumulated in excess of 1. 0 to 2. 0 m thick. From the recording of CT3, its thermal profile is unlikely to be affected by annual variations because of the snow.

Drilling and instrumentation were carried out in June 1988. The holes(50 mm in diameter) were made with water-jet drilling. The multithermistor cables were linked to a datalogger in a water-tight shelter box hung on a small tower. Almost continuous thermal data were collected at 4 or 8 h intervals from July 20, 1988, until November 4, 1998 for CT1, CT2, CT3. The accuracy of all thermistors was checked in the laboratory relative to the manufacturer's specification, and it is believed that the precision of absolute temperature readings is better than ±0.1 ℃. With the exponential relationship used for converting the resistance readings to temperature, it is believed that the precision obtained on the measurements of temperature variation is ±0.01 ℃.

4 Results

4.1 Regional climatic data

The snow thickness at CT3 from Jan. 1, 1993 to Nov. 4, 1998 is shown in Fig. 3. The climatological station, Terrasse Marine, 4.8 km away from the study site, had recorded the air temperature data from March 1989 to December 1998. Because the time series of air temperature in 1989 has gaps not to be useful, the other air temperature data are given in Fig. 4. The trend line of the time series of air temperature in the 1990's is a parabolical line of two order and it shows that the climate of study site was cooling from January 1990 to May 1993 and was warming from June 1993 to 1998. Other than 1990, 1992, 1993 and 1995 because they have gaps in time series, the mean values and covariance of the other year's time series of air temperature have been calculated. The mean values and covariances of air temperatures in 1993, 1994, 1996, 1997, and 1998 are −6.95 ℃, 219.25; −6.04 ℃, 176.22; −3.36 ℃, 116.16; −4.76 ℃, 161.66; and −3.34 ℃, 167.37, respectively. These mean values indicate that climate in northern Quebec is getting warm from 1993. From Fig. 4, it can be seen that the temperatures in summer of 1992 is lower than usual and the winter of 1992－1993 was exceptionally cold, probably in the worldwide wake of the Mount Pinatubo volcanic erruption. The air temperature covariance of 1993 is largest among all covariance. It indicates that air temperature variation is largest. This conclusion can also be found in Fig. 4.

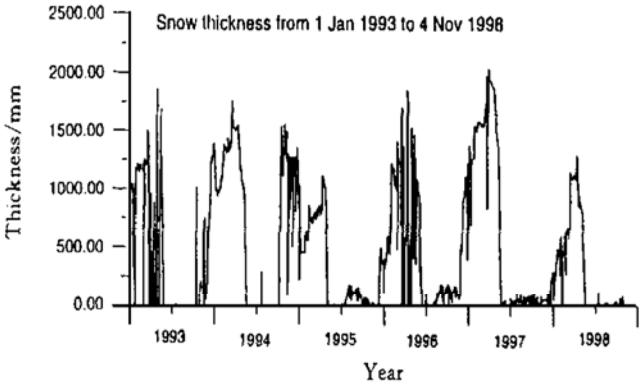

Fig. 3. Snow thickness at CT3 from 1 Jan. 1993 to 4 Nov. 1998.

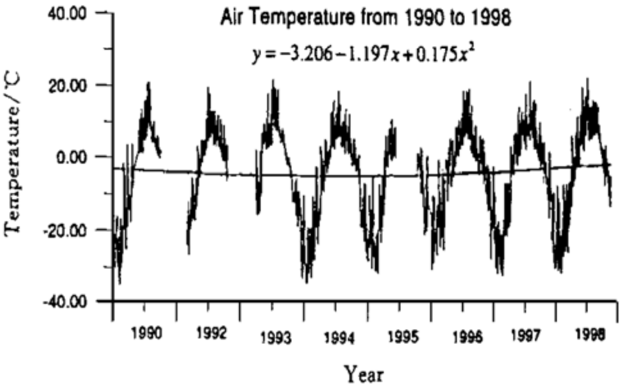

Fig. 4. Air temperature at Terrassee Marine from 1990 to 1998.

4.2 *Active layer thickness*

The thickness of active layer is mainly a function of summer temperatures. The thicknesses of active layer at CT1 and CT3 over the study period in Kangiqsualujjuaq village are given in Table 1. From Table1, it can be seen that the active layer thickness at CT3 changes very slightly and the active layer thickness at CT1 reduces from 1989 to 1994 but increases from 1994 to 1998. This phenomenon indicates that the air temperatures during a couple of days in mid- to late September are higher in 1989, 1990 and 1993. From Fig. 4, it can be seen that there are a couple of days during which air temperatures are over 20 ℃ in 1990, 1993 and 1998.

Table 1. The thicknesses of active layer at CT1 and CT3(unit: m)

Year	1989	1990	1991	1993	1994	1996	1997	1998
Active layer thickness at CT1	1. 70	1. 75	1. 60	1. 76	1. 60	1. 67	1. 67	1. 68
Active layer thickness at CT3	1. 52	1. 55	1. 43	1. 52	1. 48	1. 52	1. 56	1. 52

4.3 *Thermistor cable 1*

The time series of permafrost temperatures at depths 0. 0 m, 0. 2 m, 2. 0 m and 9. 0 m at CT1 are described in Fig. 5. From this figure, we can know that the bottom boundary of this permafrost is deeper than 9. 0 m. Fig. 5a shows that the soil temperature at depth 0. 0 m at CT1 was cooling from January 1989 to December 1991 and warming from January 1992 to November 1998. Figs. 5a and b show that the effect of snow cover on the permafrost temperature is large in 1996, 1997 and 1998, because there are only small negative temperatures in this diagram in 1996, 1997 and 1998. In fact, from Fig. 3, it can be seen that snow thicknesses in 1996 and 1997 were thicker than those in other years. Fig. 5a shows that the highest temperature at depth 0. 0 m at CT1 in 1998 is lower than that at the same position in 1993, but the highest air temperatures (Fig. 4) during summer in 1993 and 1998 are 21. 08 ℃ and 22. 42 ℃, respectively, that is, the highest air temperature in 1998 is higher than that in 1993. From Figs. 4 and 5a, it can be seen that these trend lines of air temperature and permafrost temperatures at depth 0. 0 m at CT1 have been increasing since 1993 and indicate the climate in northern Quebec is getting warm after a long time of cooling, but it is difficult to know the actual air temperature from the time series of permafrost temperature, because they are not similar. Fig. 5c shows that the permafrost temperatures at depth 2. 0 m decreased from January 1989 to December 1992 and went up from January 1993 to November 4 1998. Fig. 5d shows that the temperatures 9. 0 m deep got down from January 1 1989 to 1993 but increased from 1994 to 1998. The temperature profile from depth 0. 0 m to 9. 0 m at CT1 is given in Fig. 5e and it indicates that the permafrost temperature on April 30, 1993 is lower than those on the same days in 1989 and 1998. From the solid line in Fig. 5e, it can also be found that the permafrost temperature on September 1, 1993 was lower than those on the same days in 1989 and 1998. Therefore, Fig. 5e indicates that the climate at the study site was cooling from 1989 to 1993 and warming from 1994 to 1998.

In order to get more insight of the climate variation in northern Quebec, the freezing and thawing indexes of soil temperature at surface at CT1 have been calculated and are

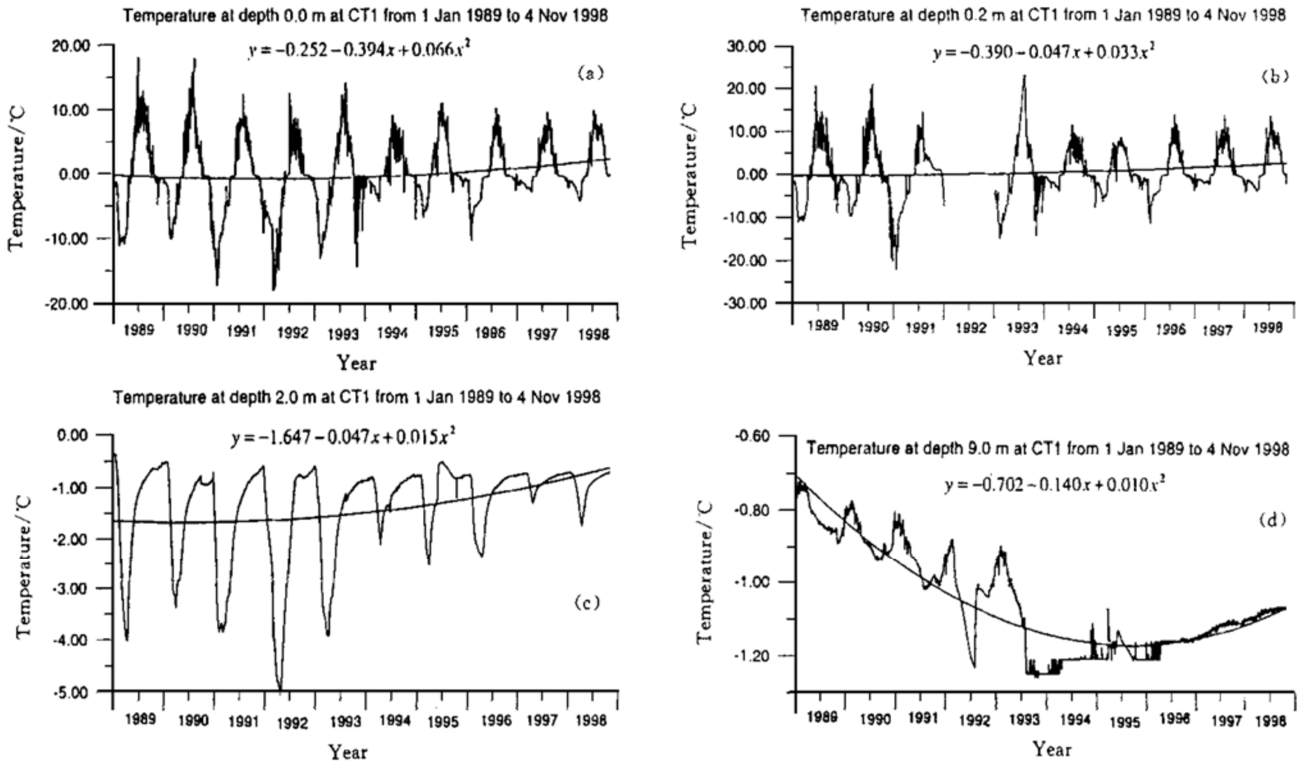

Fig. 5(a-d). Temperature records logged at CT1.

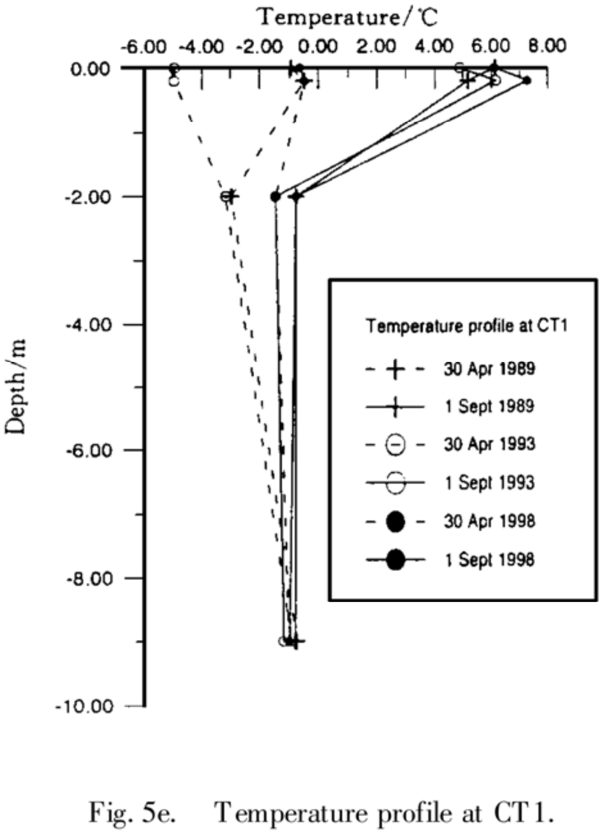

Fig. 5e. Temperature profile at CT1.

given in Table 2.

The freezing index is the yearly sum of the differences between 0 ℃ and the daily mean temperature of the days with means below 0 ℃. The thawing index, on the other hand, is the yearly sum of the differences between 0 ℃ and the daily mean temperature of the days with means above 0 ℃. From Table 2, it can be found that the freezing index of soil temperature at surface at CT1 changes from − 850 ℃ in 1989 to − 1369 ℃ in 1992 and from − 1168 ℃ in 1993 to − 279 ℃ in 1998. Table 2 also shows that thawing index of soil temperature at surface at CT1 changes from large (1064 ℃ in 1989) to small (429 ℃ in 1992) and from small (429 ℃ in 1992) to large (723 ℃ in 1998). From the thawing index, it can be seen that the summer in 1992 was a cool one. From the sum of freezing and thawing indexes, it can easily be found that the climate at northern Quebec was cooling from 1989 to 1992 and warming from 1993 to 1998 because their sum gets smaller from 1989 to 1992 and larger from 1993 to 1998, respectively.

Table 2. Freezing and thawing indexes of soil temperature at surface at CT1

Year	Freezing index (degree-days)	Thawing index (degree-days)	Sum of freezing and thawing (degree-days)
1989	– 850. 4	1064. 1	213. 6
1990	– 846. 2	947. 7	101. 3
1991	– 1261. 4	713. 8	– 547. 6
1992	– 1369. 3	429. 7	– 939. 6
1993	– 1168. 1	841. 8	– 326. 3
1994	– 281. 0	572. 0	290. 9
1995	– 476. 8	747. 4	270. 6
1996	– 617. 2	535. 2	– 82. 0
1997	– 253. 8	625. 2	371. 4
1998	– 279. 8	723. 4	443. 5

4.4 *Thermistor cable 2*

The time series of the permafrost temperature at depths 0. 0 m, 0. 2 m, 2. 0 m and 9. 0 m at CT2 are described in Figs. 6a, b, c and d, respectively. CT2 is on the top of a low hill. From Fig. 6a, we can see that there is almost no effect of snow cover on the permafrost temperature and the permafrost temperatures at depth 0. 0 m at CT2 are over 0 ℃ only during a part of summers. The highest temperature at this site is below 5 ℃ during summer and fall. The mean annual temperatures at depth 0. 0 m, 0. 2 m and 2. 0 m at this site from 1989 to 1998 is – 4. 33 ℃ , – 3. 69 ℃ and – 3. 58 ℃, respectively . The main reason is because wind strongly blows there. The absence of a meaningful snow cover is a prerequisite for having a negative mean annual temperature at the soil surface. The lack of snow cover at the site results from wind erosion and drifting. Because of the unobstructed flow of air over the plateau, snow drifting is further enhanced near ground level by the lack of a significant tree cover. Also, the snow is compacted by the wind, which increases its density and thermal conductivity. So, the temperature of permafrost body at this site is lower than that elsewhere. The permafrost body here ranges from 0. 2 m to more than 9. 0 m. Trend lines of these three time series of the permafrost temperature show that their temperatures are warming.

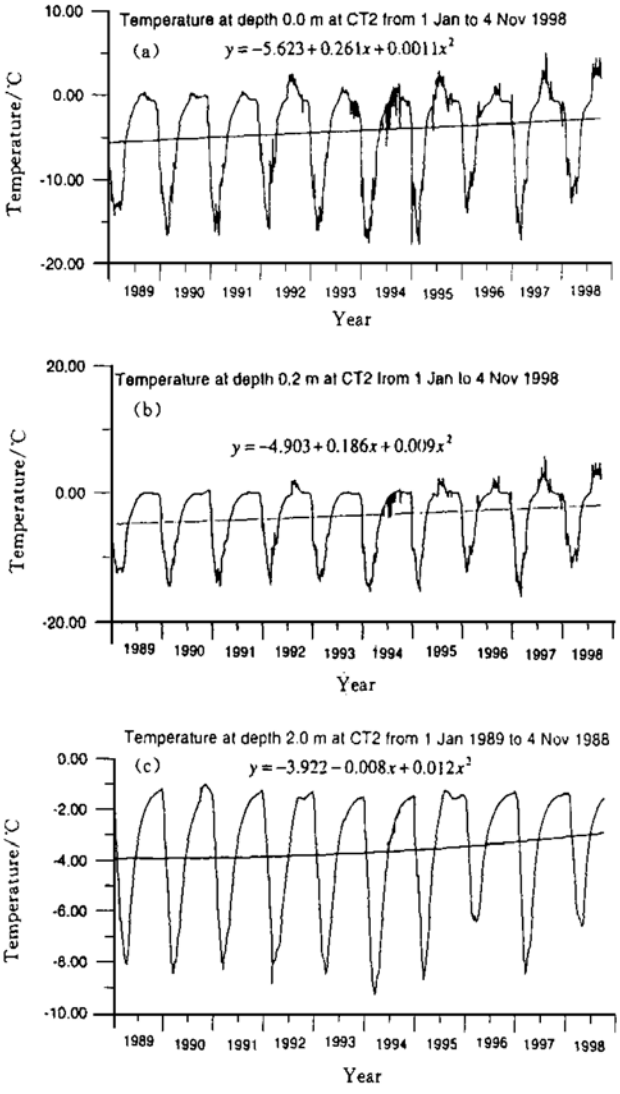

Fig. 6(a-c). Temperature records logged at CT2.

From the temperature profiles at CT2 (Fig. 6d), it can be seen that the permafrost temperatures from 0.0 m to 9.0 m deep on September 1, 1998 were higher than those on the same days in 1989 and 1993. However, the permafrost temperature at this site on April 30, 1998 was lower than those on April 30, in 1989 and 1993. This is because wind also influences the permafrost temperature at this site except that air temperature affects the permafrost temperature. The freezing and thawing indexes of soil temperature at surface at CT2 are given in Table 3.

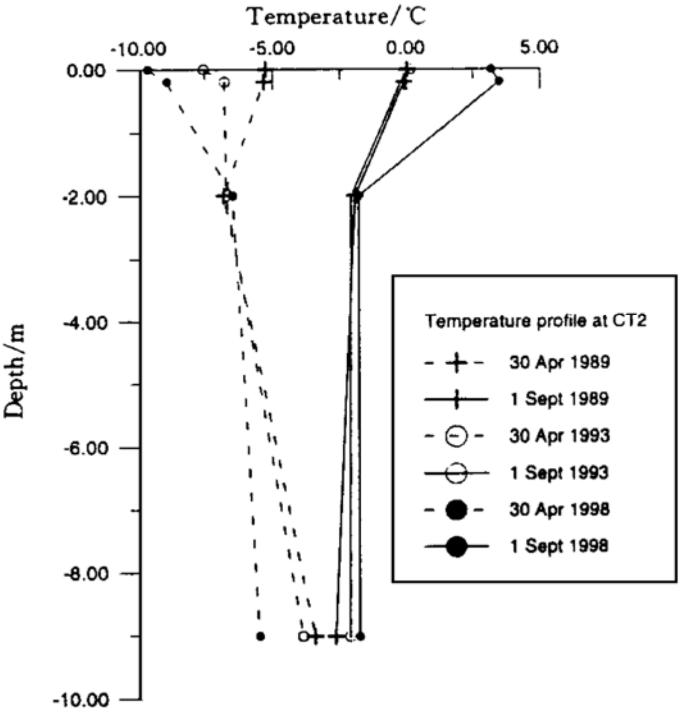

Fig. 6d. Temperature profile at CT2.

From Table 3, it can be seen that the freezing index at surface at CT2 changes from larger(− 1701 ℃ in 1989) to smaller (− 1809 ℃ in 1993) and then from smaller (− 1907 ℃ in 1994) to larger (− 1236 ℃ in 1998). The same regularity does not appear in its thawing index because it is also affected by wind but air temperature.

Table 3. Freezing and thawing indexes of soil temperature at surface at CT2

Year	Freezing index (degree-days)	Thawing index (degree-days)	Sum of freezing and thawing (degree-days)
1989	− 1701.3	2.5	− 1698.8
1990	− 1802.4	1.3	− 1801.1
1991	− 1764.7	2.2	− 1762.5
1992	− 1402.2	116.1	− 1286.0
1993	− 1809.2	15.8	− 1793.4
1994	− 1907.1	24.9	− 1882.2
1995	− 1468.0	101.4	− 1366.6
1996	− 1314.7	18.1	− 1296.6
1997	− 1560.5	122.4	− 1438.1
1998	− 1236.8	178.5	− 1058.3

4.5 *Thermistor cable 3*

The time series of the permafrost temperature at depths 0.0 m, 0.2 m, 2.0 m and 9.0 m at CT3 are shown in Figs. 7a, b, c and d, respectively. From Figs. 7a and b, it is seen that there are seldom negative temperatures in their time series. This indicates that the effect of snow cover on the permafrost temperature is large. An instrument recording snow thickness is installed at this site. The recorded snow thicknesses from 1993 to 1998 are described in Fig. 3. From Fig. 3, it can be seen that there was a lot of snow in 1994, 1995, 1996, 1997 and the recorded snow thicknesses were not zero during the summers in 1995, 1996 and 1997. The reason is maybe that the snow during those summers is not completely melt or the soil at this site is raised because of yearly frost action. Because there is a little thick cover on the thermistor at depth 0.0 m at CT3, the soil temperatures recorded by it in 1996 summer were not as high as those in 1993 summer though the air temperatures in 1996 summer were almost as high as those in 1993 summer. The snow disappeared on May 28 and began on October 26 in 1993. Without snow cover, the air temperature from June to October in 1993, such as −5.80 ℃ on September 29 and −4.65 ℃ on October 8, heavily influenced the soil surface temperatures in 1993, in which some larger negative temperatures appeared. The same situation happen in 1994. The trend lines of time series in Figs. 7a and b are almost straight lines getting up. The temperatures at depth 2.0 m and 9.0 m (Figs. 7c and d) decreased from 1989 to 1993 and increased from 1994 to 1998. Their variation likes the air temperature variation during the same period.

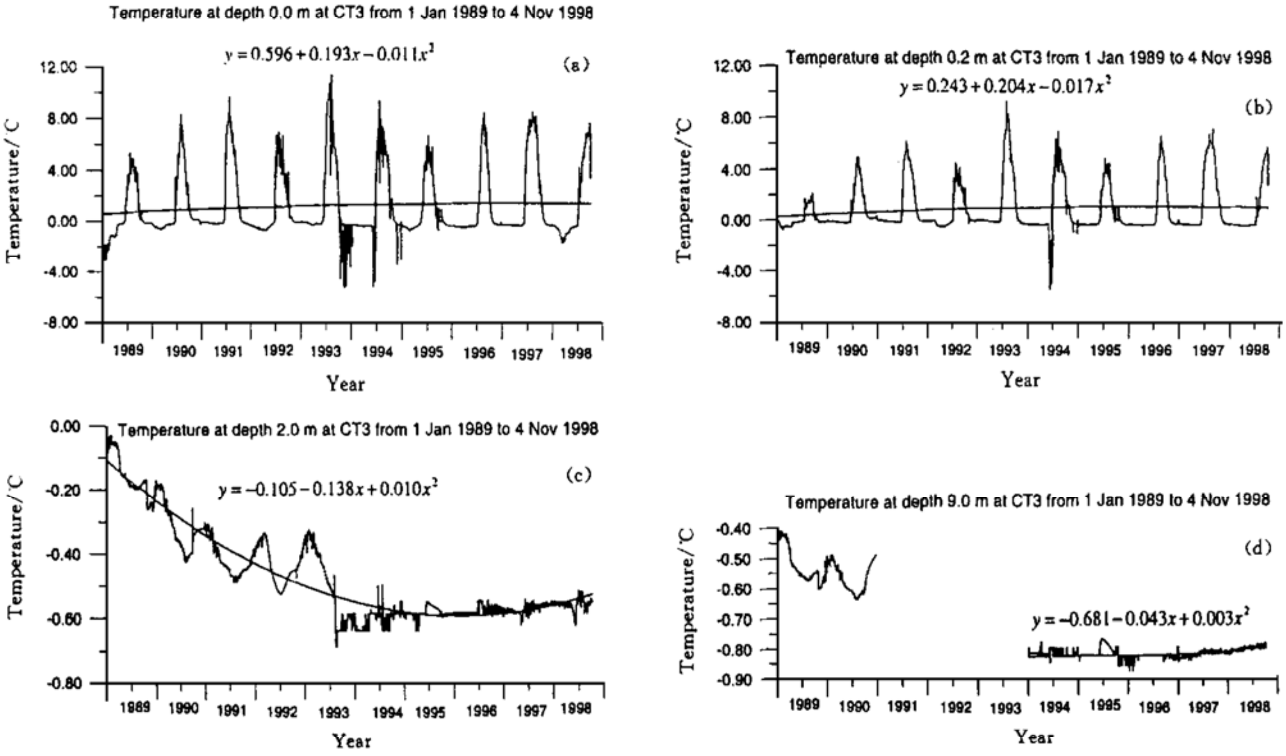

Fig. 7. Temperature records logged at CT3.

5 Discussion and conclusion

Although there are many factors, such as snow, ice cover, wind, vegetation, topography, and icefoot, that influence the thermal regime of permafrost, the principal factor is climate. It is true that the measured time series of permafrost temperatures near surface can not completely reflect the climate change in detail. For example, in spite of the gradual increase in permafrost temperature, the active layer thickness at our borehole sites did not change significantly, and although the amplitude of air temperature is getting large, the amplitude of permafrost temperature or even the temperature at soil surface, is not quickly increasing, because so many factors, especially snow, can influence the permafrost temperature. On the other hand, the measured time series of permafrost temperature basically can reflect the climate change. For example, when the air temperatures during summers in 1992 and in 1993 (Fig. 4) are low and high, respectively, the temperatures of 0.0 m deep at CT1 (Fig. 5a) and at CT3 (Fig. 7a) in 1992 and in 1993 are low and high too, respectively. When the climate was getting cooler from 1989 to 1993, most trend lines of time series of permafrost temperature (Figs. 5, 6 and 7), measured by thermistors planted in depth from 2.0 m to 9.0 m, are getting down. When the air temperatures increased from 1994 to 1998, these trend lines go up too. Therefore, the variation of permafrost temperature can basically reflect the climate change. In fact, if the study site is suitably chosen, for example, CT1, the soil temperatures near soil surface and their freezing and thawing indexes can also indicate the climate change.

From the observed data of permafrost and air temperature, and the above mention, it can be concluded that the climate along the southern shore of Hudson Strait was getting warming from 1993 after it had been cooling for a long time. This conclusion of these observation is in agreement with that all the Global Circulation Models predict an enhanced warming in polar regions associated with the increase in concentration of greenhouse gas in the atmosphere.

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