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Influence of urbanization on permafrost: a case study from Mohe County, northernmost China

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Abstract

Mohe County, northernmost China, is one of the densely populated areas in permafrost regions. The urban population has grown from about 25 000 residents in 1992 to more than 41 000 in 2011. Resident's life is closely related to permafrost environment. This paper adopted drilling, ground penetration radar, and ground temperature monitoring to investigate the permafrost in the urban area of Mohe County. The results show that the permafrost table is much lower in the urban area of Mohe County because of the urban heat island, surface disturbance of construction, space heating in winter etc. The permafrost table is 2.63–3.70 m on the edge of the urban area; the mean annual ground temperature is −1.0 to −1.33 °C. In the urban area, the maximum depth of permafrost has exceeded 15 m. The permafrost in the undisturbed area is 1.65–2.0 m, with much lower ground temperature −2.75 °C. Evidences outline a clear distribution rule that, from the edge to the center of the urban area of Mohe County, the permafrost table goes deeper and deeper, which states that the urbanization has significant influence on permafrost degradation. The degradation of permafrost in the urban area in turn has been affecting the residents' lives, such as water supply and stability of buildings.

1 Introduction

Climate warming and anthropogenic impacts will lead to extensive degradation of permafrost. Numerous studies have focused on this issue (Washburn, 1980; Nelson, 2003; Anisimov and Reneva, 2006; Harris et al., 2009; French and Shur, 2010; Romanovsky et al., 2010; Wu et al., 2010; Yang et al., 2010; Margareta Johansson, 2011; Olsen et al., 2011; Callaghan,2011; Shiklomanov and Nelson, 2013; IPCC 2013; Leopold et al., 2014). There is concern that permafrost degradation will threaten the structural stability of roads, buildings, and pipelines (Zarling et al., 1983; McFadden and Siebe, 1986; Nelson et al., 2002; Lai et al., 2004; Mazhitova et al., 2004; Wu et al., 2012; Schuur, 2013; Hong et al., 2014).

Urban permafrost is closely related to residents' lives. The effect factors relating to permafrost state are much more complex than rural. Undoubtedly, urban heat island (UHI) is one of the most important factors. UHI has been recognized and studied for at least 160 years (Howard, 1820). Heat islands in high-latitude cities are fundamentally different from those at lower latitudes. Thus far, there are only a few research works concerned to this issue. Work at Barrow, Alaska, show that the urban area averaged 2.2 °C warmer than the rural and indicate that surface temperatures and active-layer thickness are generally greater in developed areas (Hinkel, 2003; Klene, 2003). The presence and strength of the UHI in Arctic regions, has a strong seasonal component with maximum development and intensity in winter, and only weak or nonexistent expression in summer (Benson et al., 1983). Several researches at the rural area of Umiujaq, a 300-people-Inuit community, northern Quebec, evidenced permafrost degradation, and road instability (Allard et al., 2002; Buteau et al., 2004; Fortier et al., 2011).

Mohe County is in the sub-arctic zone. The urban population has grown from about 25 000 residents in 1992 to more than 41 000 in 2011. A certain climate-warming trend is obtained from the mean annual air temperature recorded on edge of urban area (Fig. 1).

The climate tendency rate in Mohe County was 0.357 °C 10 a^{-1} during the past 50 years. A concurrent trend of progressively instability of building has occurred. By now, there are no reports on the permafrost degradation and the concurrent environment, hazards issues in Mohe urban area. This paper focuses on the permafrost state in urban area. In addition, permafrost data obtained from an undisturbed site is presented to compare with the urban data. From the difference, the influence of urbanization on permafrost can be identified preliminary.

TCD
8, 4327–4348, 2014

2 Site description and methodology

2.1 Physical setting

Mohe County, the northern tip of China, is in the North Slope of Da XingAn Mountains. The longitude is 121°07′–124°20′E and the latitude is 52°10′–53°33′N. It is located in the southeastern edge of the Eurasian permafrost zone (Fig. 2). The historical data show that the annual ground temperature is about −4–0 °C in this area. The maximum thickness of permafrost is 50–100 m (Zhou et al., 2000).

Most area of Mohe belongs to hilly regions. The average elevation of Mohe is about 550 m. The highest is 1397 m. *Carex heterolep* is widely spread. The climate type of Mohe County is cold temperate continental monsoon climate. The annual average air temperature is about −4.2 °C. In spring, it is windy and warms faster. Summer is short, hot, and rainy. Temperature drops sharply in fall. Winter is long, cold, and snowy. The daily average temperature in summer is about 18.2 °C. The historical record of minimum temperature is about −52.3 °C (in 1969). The highest air temperature is 38.9 °C (in 2010). The temperature difference between day and night is big. The annual average precipitation is about 460.8 mm, and over 70 % concentrated in July Percentage of forest cover is over 90 %.

The precipitation in Mohe County is between 270–635 mm in the past 50 years. The Maximum snow cover is 2.12 m and it has an increase tendency 9.65 cm 10 a^{-1}.

There was ancient human settlement in the Paleolithic age in this area. The urban population in Mohe county was 25 000 in 1992. It increased to 41 420 in 2011. The urban area was 5.74 km^2 in 1987. The urban area was reconstructed because of the devastating fire disaster in 1987. The urban area increased to 8.74 km^2 after the reconstructing. A new 2 km^2 district was started to construct in 2011. Wood and Coal had been being used for heating in winter. Because the permafrost and clod weather, in the early, water supply was depended on shallow well which was located in kitchen where it kept warm throughout the year. Thus far, there are still many residents relying on this way for water supply.

TCD
8, 4327–4348, 2014

2.2 Methodology

Methods used for permafrost investigation of Mohe County in this paper include drilling survey, ground-penetrating radar (GPR), in-situ temperature monitoring. Nine survey sites were set at the urban area of Mohe County in 2011–2013 (Fig. 2). In addition, one comparison site was set at rural. Site I is the one that located at the undisturbed area, which is 32 km away from the urban center. Site H kept natural state before June 2012. It was surrounded by construction sites after that. Table 1 shows the details about the survey sites and the methods used.

The XY-100 drilling machine was used for the drilling survey. The depth of borehole in the urban area is 5–20 m. The borehole of site I is 70 m deep.

Thermistors are used to monitor the ground temperature. The measurement accuracy is 0.01 °C.

Ground penetrating radar (GPR) has been used extensively in areas of permafrost for subsurface investigations (Scott et al., 1990). In this paper, The GPR pulse EKKO 1000 from Sensors & Software, with 100 MHz antennas at a fixed offset of 1 m, was used for permafrost investigation. Two GPR surveys methods were applied during test. One is the fixed offset reflection profile. Another is the common mid-point (CMP) sounding (Fortier et al., 2011). The penetration depth is 10 m. The EKKO_View software is selected to plot cross-sectional GPR data images. All the GPR surveys were conducted in July 2012.

3 Results and analysis

The following presents the results obtained from the drilling survey, GPR, and temperature monitoring. The spatial–temporal comparison is used during analysis.

Figure 3 gives the GPR results of site A. Site A located to the south edge of the urban area of Mohe County. The *Carex heterolep* cover was removed for building construction in early 2011. In some places, where the organic mat was not removed completely, sparse grass grows again.

According to the analysis of the CMP sounding carried out in this study area, a constant value of 0.075 m ns^{-1} was used to produce the depth profiles in Fig. 2. The start point 0 m is the foot of an unpaved road for construction. The embankment of the road is 0.6 m high, 5 m wide. The other span is covered by *Carex heterolep*. The topography correction has been done for the travel time-depth profile.

In Fig. 3, the red curve is the determined thawing depth. The data shows that the thawing depth of the natural ground at this time is about 2.0 m. The monitored ground temperature data of site H gave a thawing value 63 cm from 17 July 2012 to 15 October 2012. Referring to this thawing velocity, the maximum thawing depth of site A can reach to 2.63 m on 15 October 2012.

Figure 4 illustrates the GPR survey result of site D. Site D is a concrete runway in a high school. A 10 m deep borehole was drilled at the 31 m position, which was drilled in March 2012.

According to the analysis of the CMP sounding carried out in this study area, a constant value of 0.071 m ns^{-1} was used to produce the depth profiles in Fig. 4. The data shows that there is no frozen soil layer exists within the survey depth at this site. The drilling survey presented the same result.

Figure 5 presents the ground temperature profile and the strata at site E. the depth of the drilling hole for temperature monitoring is 17.3 m. The borehole was drilled on 13 July 2012. A GPR survey profile was conducted on 15 July 2012, which went across the drilling hole.

Site E located on the northwest edge of the urban area of Mohe County. The ground surface is covered by planted grass. The drilling survey revealed that the type of permafrost of this site is ice-poor. It is layered cryostructure. The thickness of ice is 0.1–0.5 cm. The ground temperature curves show that the permafrost table is 3.7 m. The temperature at the depth 15 m is −1.26 °C. The GPR result shows that the thawing depth was about 3.1 m on 15 July 2012. Same as site A, referring to the thawing velocity of site I, the maximum thawing depth of site E can reach to 3.73 m on 15 October 2012. It can be seen that the GPR result and the monitoring result are almost identical.

Figure 6 presents the ground temperature profile of site B. This site is a space surrounded by new buildings. The surface is covered by *Carex heterolep* and construction waste. There are three boreholes were drilled at site C in August 2013. The three boreholes arranged in a straight line. The borehole of Fig. 6b is in the middle. The interval between holes of Fig. 6a and b is 20 m. The interval between holes of Fig. 6b and c is 65 m.

The borehole of Fig. 6a is 15 m deep, which is near to a street, covered by construction waste. The steady ground temperature at 15 m deep is 1.11 °C. In Fig. 6b, the borehole is covered by *Carex heterolep*. The steady ground temperature at 15 m deep is 0.16 °C. According to the temperature gradient of this area, the calculated maximum thawing depth is about 16 m. In Fig. 6c, the depth of the borehole is 10 m, which is covered by *Carex heterolep* too. The temperature at 10 m deep is 0.25 °C. The calculated maximum thawing depth is about 14 m according to the temperature gradient of this area. The maximum freezing depth is about 4.0 m in this area. Therefore, it can be considered that residual thawed layer exists in the urban area, which is unrefrozenable.

Figure 7 presents the ground temperature profile of site C.

Site C is a sidewall in a community, paved by concrete. Three boreholes were drilled in July 2010. Their ground temperature profiles are almost the same. A seven-floor building that is four meter away from the boreholes has appeared serious differential settlement and cracks on the walls (the widest crack has reached to 9 cm), which is mainly caused by the settlement of permafrost foundation. Figure 7 shows that the temperature at the bottom of the borehole is about 4.41 °C. As shown in Fig. 6a, the temperature at 8 m deep is 3.58 °C. Therefore, it can be guessed that the maximum thawing depth of permafrost at site C is over 16 m. The 50 m-long GPR test profile shows that there is no permafrost within the investigated depth at this site too.

Figure 8 is the ground temperature profile of site H. Site H located in the new district, to the east of the old urban area of Mohe County. It is about 1.89 km away from

TCD
8, 4327–4348, 2014

site C. The ground surface is covered by *Carex heterolep*. This place was planed as greenspace of the new district. It can be looked as an undisturbed site before 2012. The new district was started to construct in 2011. Now, it is surrounded by buildings.

In Fig. 8, the borehole for ground temperature monitoring was drilled on 27 April 2011, which is 15 m deep. The ground temperature curves show that the permafrost table is 1.65 m in 2012. It is 2.0 m in 2013. The temperature at the depth 15 m was −1.16 °C in 2012. It has a little increase in 2013. It was 1.00 °C in 2013. It can be seen that construction of the new district already has a significant effect on permafrost degradation in a short span of two years.

Site F is in the north of the urban area of Mohe County. It locates at a farmland, which is being changed to residential block. Eight boreholes were drilled in July 2010. The drilling depth is from 5–15 m. All the drilling survey results reveal that there is no frozen ground layer within the surveyed depth at site F.

Site G is in the east of the urban area of Mohe County. It was an old shantytown and was removed in 2010. GPR surveys were conducts here and the results show that there is no permafrost layer within the surveyed depth at site G.

Figure 9 is the ground temperature profile and strata of site I. This site is used to as a comparing site. Site I is about 32 km away from the urban area. It is not impacted by human activity. The ground surface is covered by intensive *Carex heterolep* and small shrubs.

In Fig. 9, the 70 meter-deep borehole was drilled in October 2010. The drilling survey reveals that the permafrost at this site is icy. The ground temperature profile shows that the permafrost table is about 2.0 m. The ground temperature at 15 m deep is −2.73 °C. It is −2.11 °C at 70 m deep. According to the ground temperature gradient interval 1–3 °C 100 m^{-1}, the maximum thickness of permafrost is during 140–281 m, which is much deeper than the reference recorded (Zhou et al., 2000). The ground temperature at this site is much colder than that in the urban area of Mohe County.

4 Discussions and conclusions

This study firstly investigated the permafrost in the urban area of Mohe County, northernmost China. The methods composed of drilling, GPR, ground temperature monitoring can reveal the current state of the permafrost in the urban area. Further, the comparison with the rural can show effect of urban heat island (UHI).

In the early stages, most of the urban area was shantytown. The base of the houses is not elevated, which is different from buildings of the native community in Alaska, northern Canada. There, buildings are built on wooden pilings and elevated 1–2 m above the ground surface, which can minimize the impact of heated buildings on the ground thermal regime, and prevent differential ground subsidence known as thermokarst. It is very cold in Mohe County in winter. The house was heated by burning wood or coal to maintain interior building temperatures at 24–28 °C. Together with the improper base structure, lots of heat was inputted into the ground. For this reason, many buildings has occurred cracks and settlement. There is another problems has occurred. The residents have been getting in trouble with water supply. The old water supply way, mentioned in the end of the "physical setting" part of this paper, is being threatened now. The degradation of permafrost caused descending of groundwater level, which leads the old shallow well cannot supply water steadily anymore. Residents have to build new deeper well for steadier and cleaner water.

The factors caused the permafrost degradation in the urban area of Mohe include the urbanization, climate warming etc. The devastating fire disaster in 1987, almost burning the whole city, might affected the permafrost too. However, the individual characteristics of these factors, and their effecting process and magnitude on permafrost are not concerned in this study. These should be studied in further work.

With the keeping growing of urban population and extending of urban area, the building stability and water supply problems caused by permafrost degradation will become more serious. This should be eagerly studied to safeguard the residents' lives and safety.

TCD
8, 4327–4348, 2014

Analysis of ground temperature, GPR, and drilling yields the following preliminary conclusions:

1. the permafrost table in the undisturbed area is about 1.65–2.0 m, with much lower ground temperature.
2. The permafrost table is 2.63–3.7 m on the edge of the urban area.
3. Strong permafrost degradation has been occurring in the urban area of Mohe County. The maximum degradation depth of permafrost has exceeded 15 m.
4. The evidence suggests that urbanization has contributed to permafrost degradation in the urban area of Mohe County. From the rural to the urban center, the maximum thawing depth of permafrost becomes more and more deep.

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TCD
8, 4327–4348, 2014

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TCD
8, 4327–4348, 2014

Influence of urbanization on permafrost

W. B. Yu et al.

Table 1. Survey sites and methods adopted.

Survey sites	A	B	C	D	E	F	G	H	I
Drilling survey	×	√	√	√	√	√	×	√	√
GPR and date	√	√	√	√	√	×	√	×	×
Temperature monitoring	×	√	√	×	√	×	×	√	√

Notes: the symbol "×" stands for no and the symbol "√" stands for yes.

TCD
8, 4327–4348, 2014

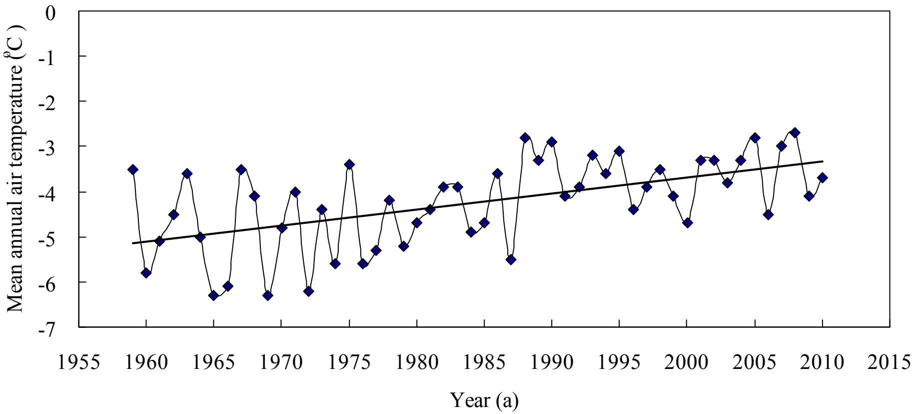

Figure 1. Mean annual air temperature at Mohe County.

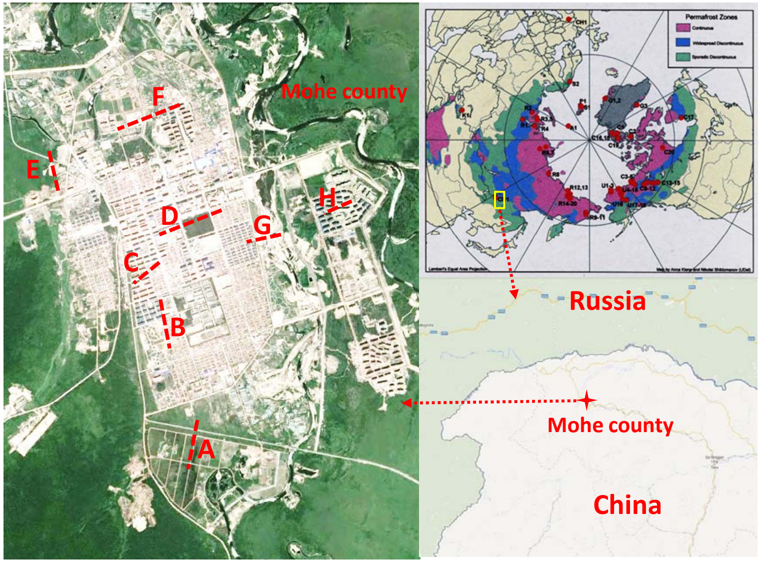

Figure 2. Location of temperature monitoring, GPR, and drilling sites in the study area.

TCD
8, 4327–4348, 2014

TCD
8, 4327–4348, 2014

Influence of urbanization on permafrost

W. B. Yu et al.

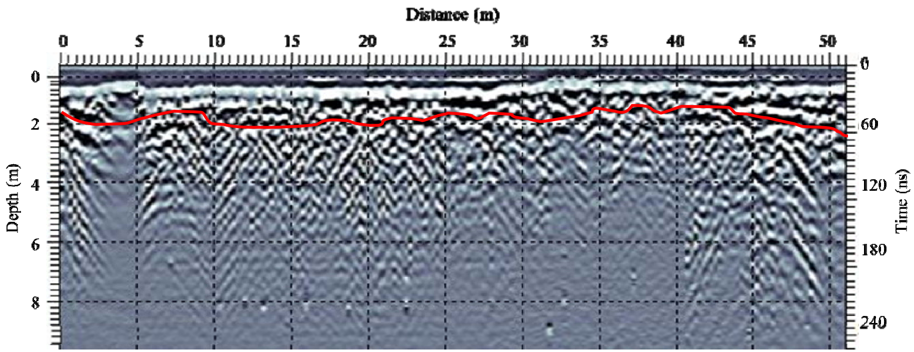

Figure 3. GPR reflection survey profile at site A (conducted on 15 July 2012).

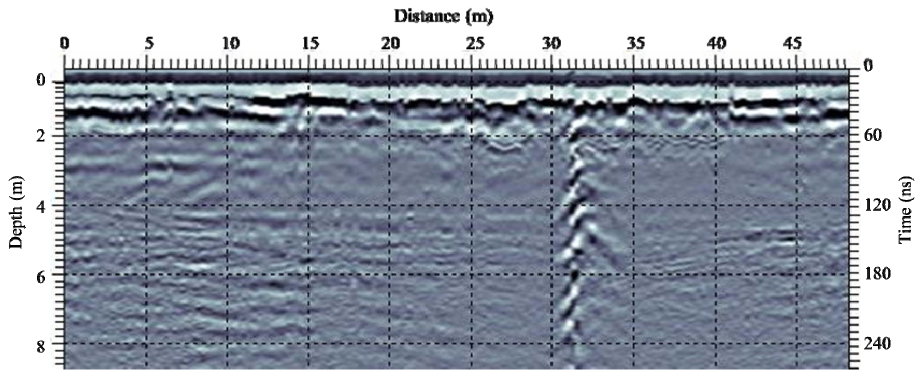

Figure 4. GPR reflection survey profile at site D (conducted on 14 July 2012).

TCD
8, 4327–4348, 2014

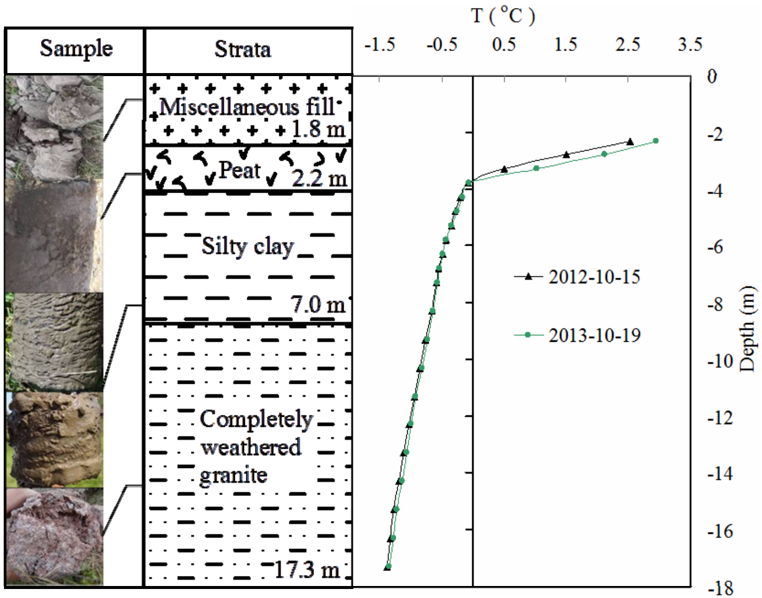

Figure 5. Ground temperature profile and strata at site E.

TCD
8, 4327–4348, 2014

Influence of urbanization on permafrost

W. B. Yu et al.

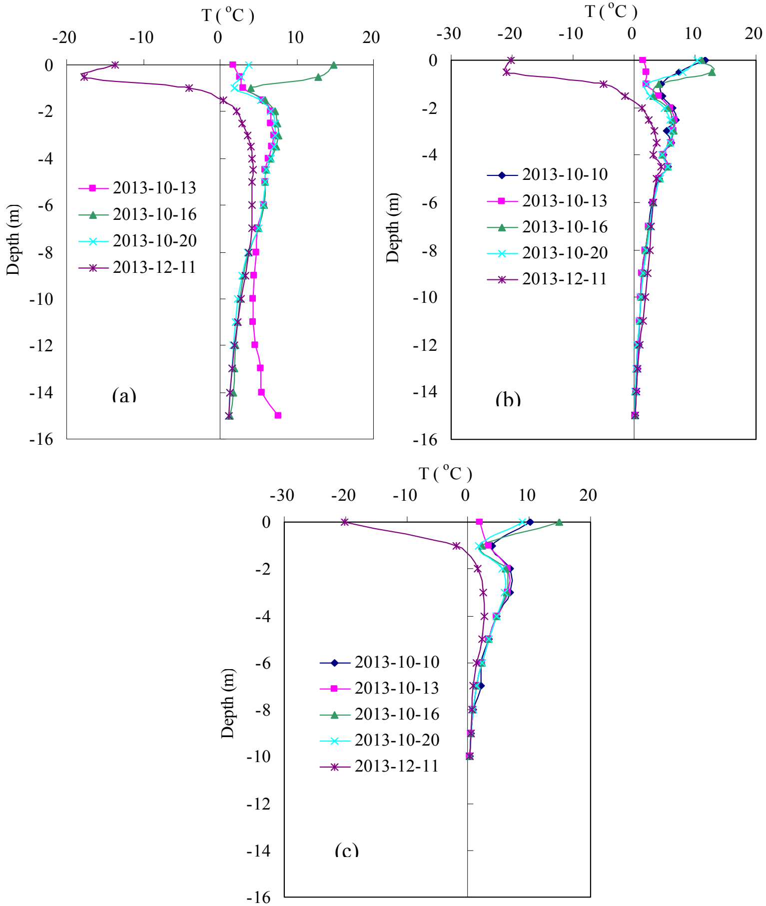

Figure 6. Ground temperature profile of site B.

TCD
8, 4327–4348, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

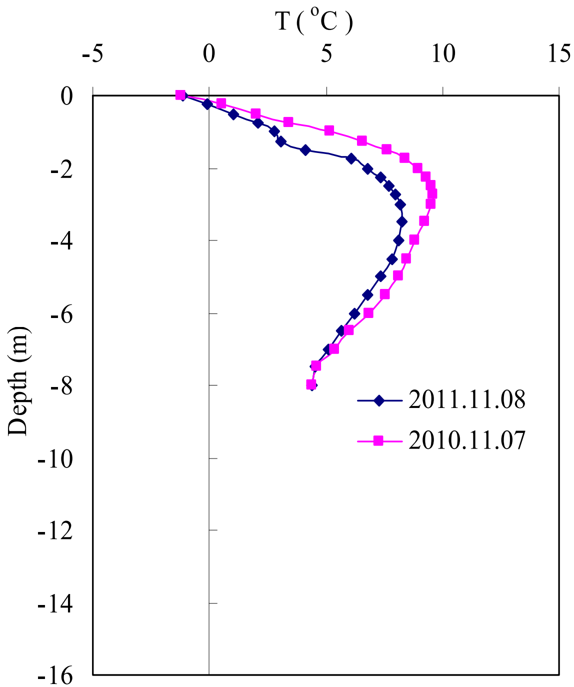

Figure 7. Ground temperature profile of site C.

TCD
8, 4327–4348, 2014

Influence of urbanization on permafrost

W. B. Yu et al.

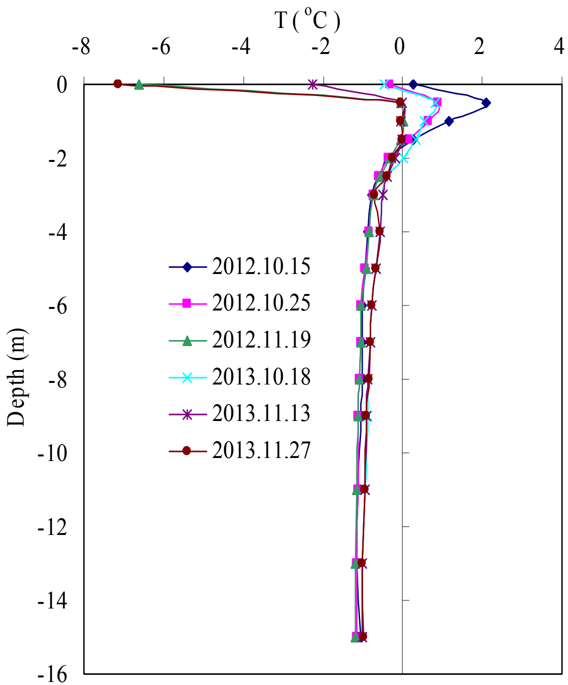

Figure 8. Ground temperature profile of site H.

TCD
8, 4327–4348, 2014

Influence of urbanization on permafrost

W. B. Yu et al.

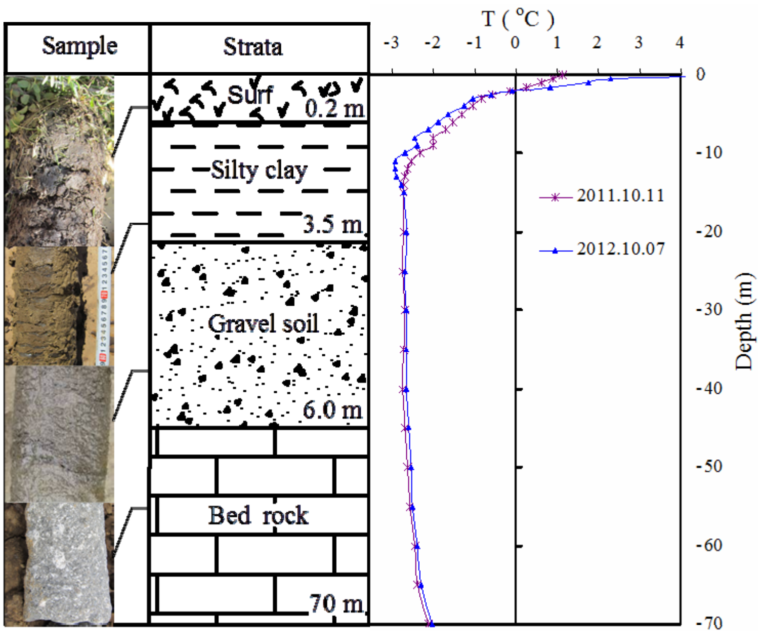

Figure 9. Ground temperature profile and strata at site I.