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SIMULATION OF THE THERMAL REGIME OF PERMAFROST IN NORTHEAST CHINA UNDER CLIMATE WARMING

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Abstract

Numerical simulation indicates that the geothermal regime of permafrost in northeast China will change as air temperature continuously rises. Calculated results show that, when the initial surface mean annual temperatures, T_s, are 0.5, 0.0,-0.5,-1.5,-2.5, and -3.5ºC and the annual range of surface temperature is 52ºC, the mean annual ground temperatures at a depth of 14 m will correspondingly be -0.16, -0.70, -1.17, -2.10, -3.03, and -4.05ºC, and the permafrost thicknesses respectively will be 16.9, 28.3, 38.3, 58.9, 81.3 and 121.5 m under equilibrium between the climate and permafrost thermal regimes. Fifty years later, the predicted temperatures at a depth of 14 m will rise to 0.0, 0.0, -0.17, -0.94, -1.83 and -2.83ºC under the conditions assumed. When Ts is lower than -0.5ºC, the depth to the permafrost table will increase by about 20 cm. If future air temperatures rise at a rate of 0.04ºC/a or less, and the ground surface temperature changes at same rate, the decrease in the area of permafrost in Northeast China will be within the limits of the region where the mean annual surface temperature in the existing permafrost area is higher than 0ºC.

Introduction

Changes in the thermal regime of permafrost are generally determined by climatic processes under natural conditions and climatic or ground surface changes caused by human activities. One of the latter concerns is global climatic warming caused by increasing concentration of greenhouse gases in the atmosphere. Scientists predict that climate warming caused by man's activities will far exceed those from natural processes during the next century. The IPCC impact assessment on climate change (1990) gives a consequent increase of the global mean annual temperature in the range of 1.5ºC to 4~5ºC for a doubling of CO_2 in the atmosphere between now and the years 2025 to 2050 under a "business-as-usual" scenario. The 1995 report predicts a rise in the global mean surface temperature of about 1~3.5ºC using climate models that take into account greenhouse gases and aerosols by 2100 (IPCC, 1996).

Climate warming could result in an increase in active layer thickness overlying permafrost, a rise in ground temperatures, and thinning of permafrost. Research concerning future changes in the geothermal regime of permafrost is therefore important for analyzing present construction, determining design principles for different types of construction, and determining its influence on the geological environment under a warming climate.

The response of permafrost thickness and ground temperature to climate change under continuous warming is likely to be disequilibrium. Changes in the permafrost geothermal regime are dependent not only on an increase in air temperature, but also on (1) the ground moisture content, including ice and unfrozen water, the thermal conductivity and specific heat capacity of frozen and unfrozen ground, (2) the geothermal gradient below the permafrost base, (3) the annual range of air temperature changes in the local regions, and (4) the ground surface conditions. Therefore, the response of permafrost to climatic change will differ in different sectors of the same region and in different regions.

The following scenario was used to simulate future changes in the thermal regime of permafrost in northeast China. (1) The air temperature rises at a rate of 0.04ºC per year; the ground surface temperature rises at same rate. (2) Based on meteorological observatories in the region, the average annual range of ground surface temperature is 52ºC. (3) The study region contains soil layers that are homogeneous. (4) The geothermal regime of the permafrost is in equilibrium with the existing environment.

Mathematical description

Under natural conditions, the permafrost temperature field, with change, can be described by the following differential equations and boundary and initial conditions:

$$C_f = \frac{\partial T_1}{\partial t} = \frac{\partial}{\partial x}\lambda_f \frac{\partial T_1}{\partial x} \quad [1]$$

$$C_u \frac{\partial T_2}{\partial t} = \frac{\partial}{\partial x}\lambda_u \frac{\partial T_2}{\partial x} \quad [2]$$

$$T(0,t) = f(t) \quad [3]$$

$$T(x,0) = g(x) \quad [4]$$

$$T_1(x,t)\big|_{x=\xi} = T_2(x,t)\big|_{x=\xi} = T_f \quad [5]$$

$$\lambda_f \frac{\partial T_1}{\partial x}\bigg|_{x=\xi} - \lambda_u \frac{\partial T_2}{\partial x}\bigg|_{x=\xi} = L\gamma_d (W - W_u)\frac{d\xi}{dt} \quad [6]$$

$$T_1(x,t)\big|_{x=\xi_d} = T_2(x,t)\big|_{x=\xi_d} = T_f \quad [7]$$

$$\lambda_f \frac{\partial T_1}{\partial x}\Big|_{x=H} = q \quad [8]$$

$$\lambda_f \frac{\partial T_1}{\partial x}\bigg|_{x=\xi_d} - \lambda_u \frac{\partial T_2}{\partial x}\bigg|_{x=\xi_d} = L\gamma_d (W - W_u)\frac{d\xi}{dt} \quad [9]$$

where λ_f, λ_u are the thermal conductivities of frozen and thawed ground (W/m K); C_f, C_u are volumetric heat capacities of frozen and thawed ground (kJ/m^{3o}C); γ_d is the dry density of the ground (kg/m^3); T_1, T_2 are the temperatures of the frozen and thawed ground (ºC); T_f is the freezing point (ºC); W, W_u are the total water content and unfrozen water content of the ground (%); x, t are the spatial and temporal coordinates (m, h); H is the depth in the calculated region (m); ξ is the phase change front (m); and ξ_d is the permafrost base. Equations (1)-(9) were solved by numerical methods. The thickness, H_1 of the upper layer equals 5 m. In the layer, W=17%, W_u=3%, γ_d =1600, γ_f =1.57, γ_u =1.28, C_f =1872, C_u = 2475. In the lower layer, H_2, W=6%, W_u =1%, γ_d =1600, γ_f =1.61, γ_u =1.28, C_f =1411, and C_u =1673. The thickness of the layer is determined by the permafrost thickness. Let upper and lower boun dary conditions be f(t) and q:

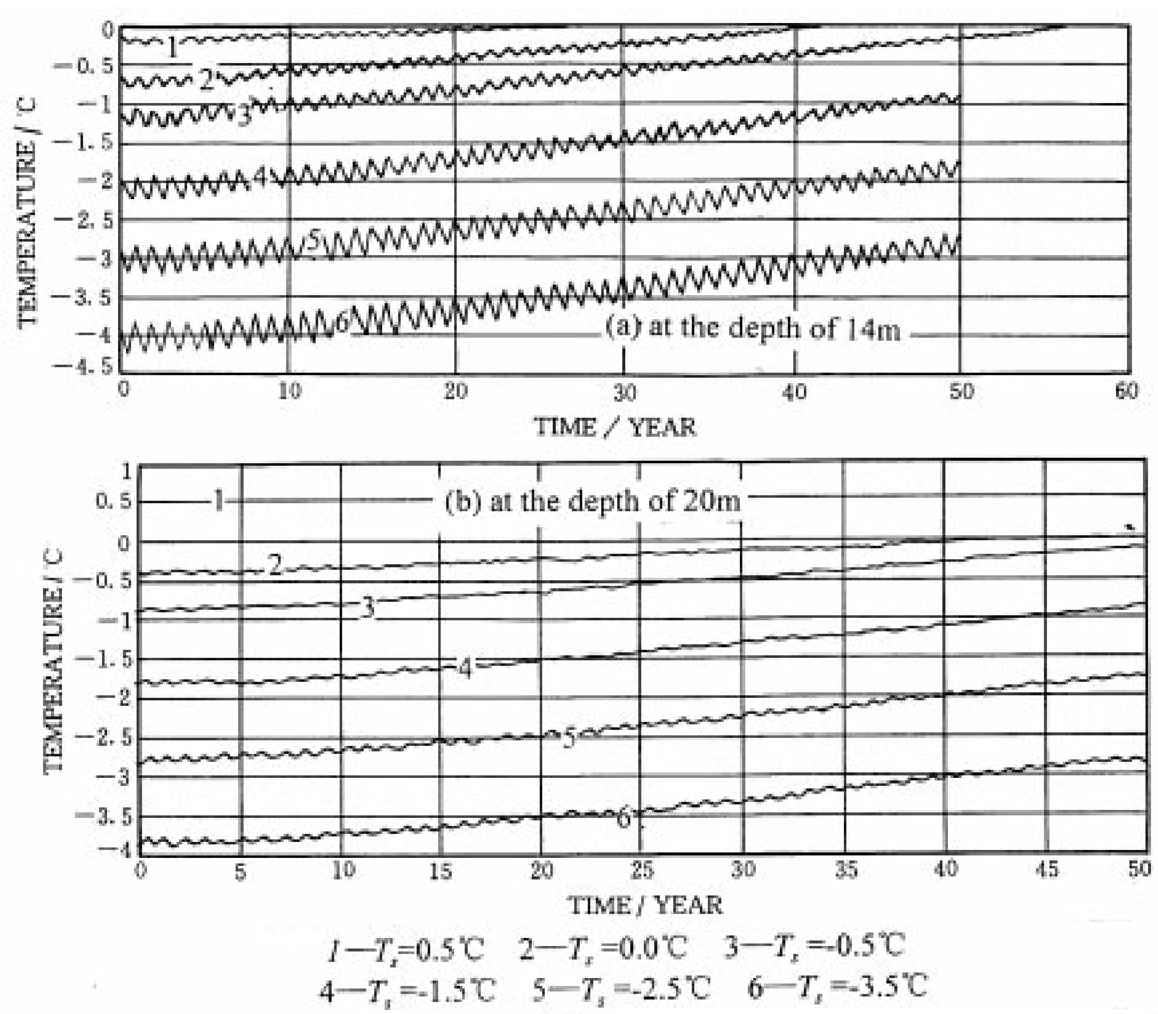

Figure 1. Changes in simulated ground temperature with time at depths of (a) 14 m and (b) 20 m, for different values of T_s. 1: T_s =0.5ºC; 2: T_s =0.0ºC; 3: T_s =-0.5ºC; 4: T_s =-1.5ºC; 5: T_s =-2.5ºC; 6: T_s =-3.5ºC.

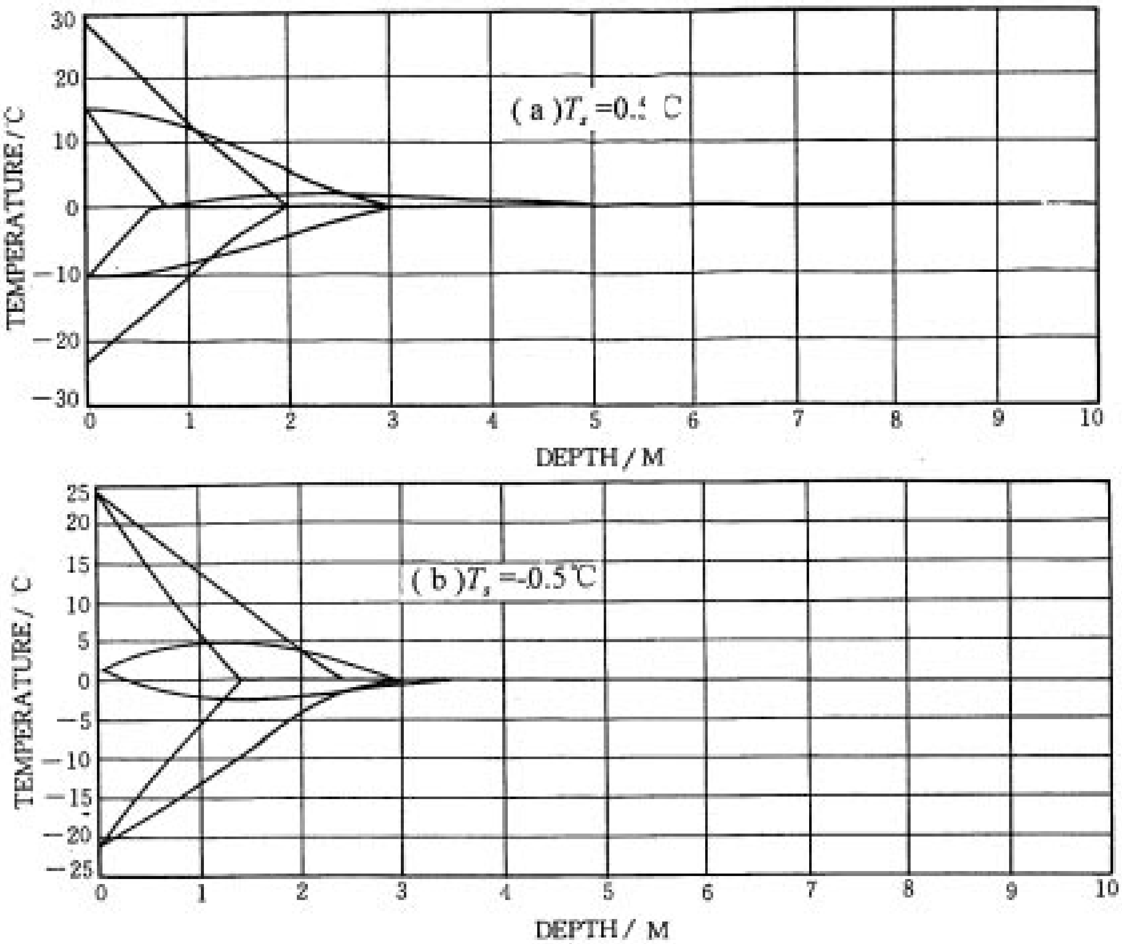

Figure 2. Simulated ground temperature profiles in the 50th year.
(a) T_s =0.0°C; (b) T_s =-0.5°C.

$$f(t) = T_s + G_1 t + A_0 \sin\left(\frac{2\pi}{8760}\right) \qquad [10]$$

$$q = \lambda_u G_g \qquad [11]$$

where G_t =0.04°C/8760 h, the rate of increase in the air temperature; G_g (0.04°C/m) is the geothermal gradient of the thawed ground below the base of permafrost; A_0 (26°C) is one-half of the annual range of the ground surface temperatures; T_s is the initial mean annual ground surface temperature.

Calculated results

The permafrost in Northeastern China underlies about 39,000 km^2 and occurs north of 45°N and between 131°E and 116°E. Ground temperatures at the depth of zero annual amplitude range from 0 to about -4.2°C. To determine the future permafrost geothermal regime under a warming climate, equations (1)-(9) were solved by finite difference methods for T_s =0.5, 0.0, -0.5, -2.5 and -3.5°C. In the initial state, the permafrost thicknesses for these values are, respectively, 16.9, 28.3, 38.3, 58.9, 81.3, 121.5 m. The calculated results show that: (1) under the assumed condition, the T_s boundary between permafrost and seasonally frozen ground is 0.5°C or higher; (2) in comparison to heat conduction without phase change in the ground, the depth of zero annual amplitude of ground temperature in permafrost depends on T_s in addition to the factors affecting the depth of the zero annual amplitude temperature change in unfrozen ground (Kydeliaftref, 1992); and (3) the amplitude of temperature change decreases with increasing depth (Figure 1). When a year-round suprapermafrost talik develops, significant annual temperature fluctuations no longer penetrate into the permafrost (Figure 1, T_s =0.5 and -0.5°C)

When T_s =0.0°C and -0.5°C, the changes of ground temperatures with depth in the 50th year at different times are shown in Figure 2. The profiles of ground temperatures in the figure show that, when T_s =0.0°C, a talik develops between the permafrost and the active layer (Figure 2a). When T_s =-0.5°C, the frozen ground maintains contact with the active layer in 50th year

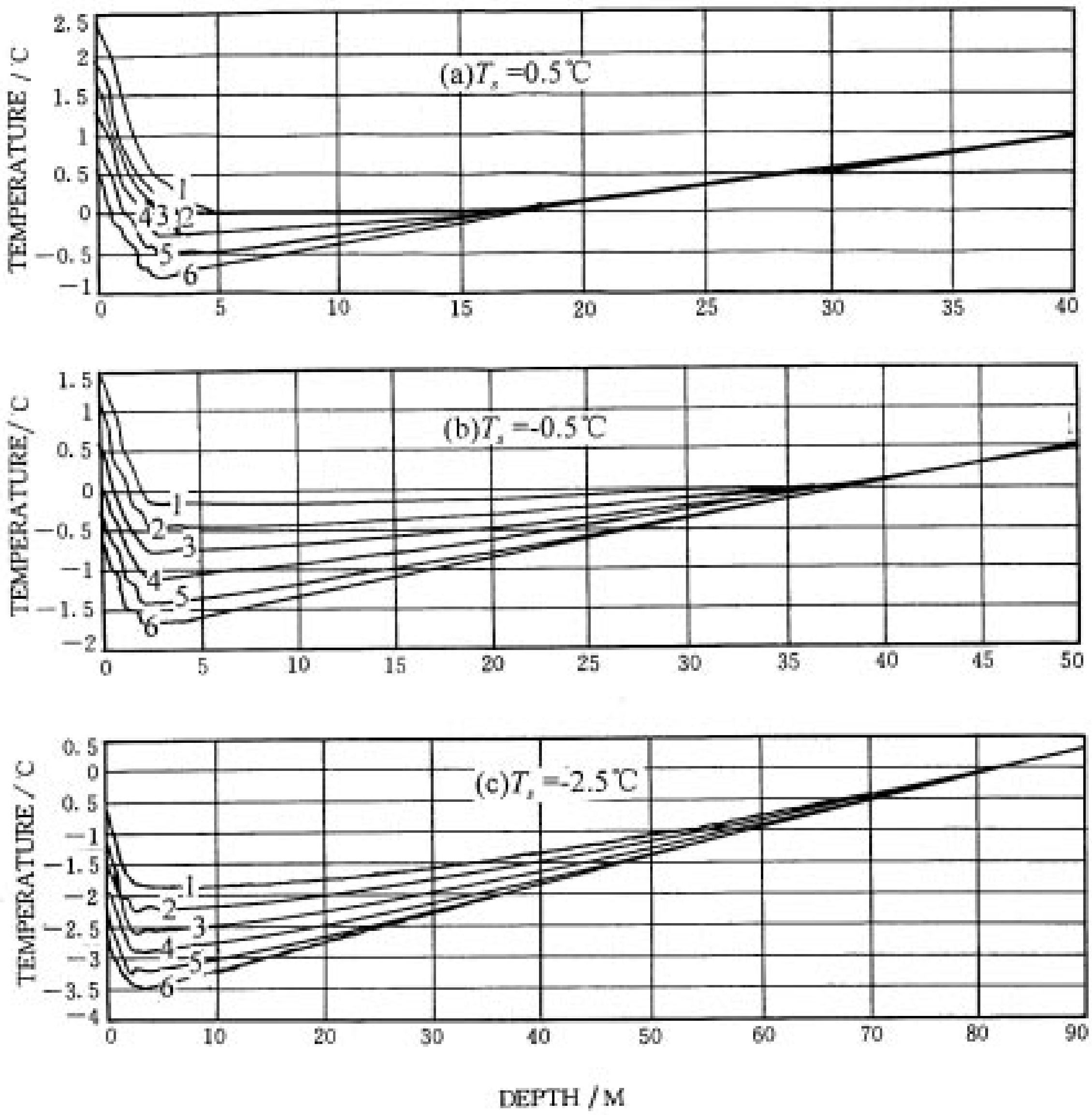

Figure 3. The profiles of the mean annual ground temperatures for different times.

(Figure 2b). Therefore, the permafrost deteriorates into seasonally frozen ground, only if the present surface temperature of the permafrost is higher than -0.5ºC. An analogous simulation (Li et al., 1996) for the permafrost on the Qinghai-Xizang (Tibet) Plateau shows that, when T_s is higher than -1.1ºC, 50 years later the permafrost degrades and some permafrost taliks develop. There A_0 =13°C, half that of northeastern China. Therefore, a more stable geothermal regime in permafrost will result in northeastern China than on the Qinghai-Xizang (Tibet) Plateau because the annual range of air and ground surface temperatures in Northeast China is higher than those on the Qinghai-Xizang Plateau.

Under a climatic warming scenario, although the rate of permafrost degradation in higher-temperature frozen ground will be more rapid than in lower-temperature frozen ground, the rate of temperature rise is slower than in the lower-temperature frozen ground (Figure 3). For T_s =0.5, 0.0, -0.5, -1.5, -2.5, -3.5ºC under the given conditions, the initial mean annual temperatures at the depth of 14 m are correspondingly 0.16, -0.70, -1.17, -2.10, -3.03 and -4.05ºC; and the permafrost thicknesses are respectively, 16.9, 28.3, 38.3, 58.9, 81.3, 121.5 m. The calculated results indicate that, 50 years later, the temperatures at a depth of 14 m will rise to 0.0, 0.0, -0.17, -0.94, -1.83 and -2.83ºC, and the thicknesses of permafrost will decrease to about 14.0, 25.7, 36.1, 58.8, 81.3 and 121.5 m.

Conclusion

Based on analysis of the factors affecting the permafrost geothermal regime and the calculated results, the following conclusions are reached.

1. In comparison with heat conduction without phase change in the ground, the depth of zero annual amplitude temperature change in permafrost depends on T_s in addition to other factors affecting the depth of the zero annual amplitude temperature change in unfrozen ground. The amplitude of the ground temperature decreases with increasing depth. When the permafrost becomes detached from the seasonally frozen ground (i.e., a supra-permafrost talik is present), the depth of annual temperature fluctuation does not penetrate below the top of the permafrost table. When the permafrost is contiguous with the active layer, the depth of the annual temperature fluctuation normally does not penetrate to the permafrost base.

2. Because of the influence of the phase change, the sensitivity of the ground temperature will be lower with a rising temperature in the frozen ground under climatic warming. But, since the permafrost thickness will thin with the rising temperature, the depth of the annual temperature fluctuation normally does not penetrate to the permafrost base.

3. Since the thermal conductivity of the ground is low, changes in permafrost geothermal regime will not equal those in other climatic environments under a continuously changing climate where air and ground surface temperatures will increase more rapidly than those in permafrost.

4. Because the thermophysical properties of frozen ground and unfrozen ground are different, the stability of the permafrost geothermal regime will be less with a smaller annual range of air and ground surface temperatures under a climatic warming scenario.

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