Variability of Thaw Depth Depending on Surface Micro-undulation and Vegetation Cover in the Siberian Tundra

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ABSTRACT

The Siberian tundra occurs in a permafrost area that is overlaid with a thin surface layer that freezes and thaws annually. The runoff and subsurface storage in the tundra watershed might be controlled by spatial and temporal variation in the ground freezing and thawing processes. To understand the spatial variation in thaw depth in a tundra watershed near Tiksi, Siberia, ground surface level, thaw depth, and vegetation cover were investigated in the summer of 1999. The thaw depth in this area varied between 0.3 and 1 m. The direction of runoff was determined by analyzing micro-undulations on the ground surface. The ground thawed to a comparatively shallow depth on long slopes, and to a greater depth at or near water-filled micro-depressions. The depth of thaw also varied with the vegetation cover: it was shallower in moss-covered areas and deeper near frost boils. The influences of micro-undulation and vegetation cover on the spatial variation of thaw depth are discussed. Our results imply that the spatial variation of thaw depth in a tundra watershed can be estimated using surface information, such as topography and vegetation.

Introduction

Hydrologic processes in the Arctic tundra play an important role in global climate (Kane, 1997). Siberian tundra occurs in a permafrost area that is overlaid with a thin surface layer that freezes and thaws annually. When the ground thaws, the ice in the soil melts, but cannot drain by downward infiltration because of the low hydraulic conductivity of the underlying permafrost (Bridges, 1990). Once water is supplied, it flows laterally through the thawed surface layer, and the flow is controlled by soil horizons and the slope of the surface layer (Hinzman *et al*., 1991). To characterize arctic hydrologic processes, such as runoff and subsurface storage, it is important to clarify the characteristics of the depth of thaw in the ground as it increases through the thaw season.

Ground thawing is affected not only by the physical properties of soil, but also by the surface energy balance and water movement through the soil. Soil texture, moisture content, vegetation, and evapotranspiration are spatially variable due to surface undulations, and may further influence the runoff and subsurface storage of tundra watersheds. Mizoguchi *et al*. (1999) described the spatial variation of thaw depth in a tundra slope, caused by variations in the elevation of the ground surface and by the vegetation cover. Watanabe *et al*. (2000) reported that the depth of thaw in tundra decreased with increasing thickness of the live-plant layer. However, little is known about the relationships between surface micro-undulations, vegetation cover, and thaw depth.

In this study, we report the spatial variation of thaw depth of a tundra watershed. Then, we discuss its relationship with the micro-undulations and vegetation cover of the ground surface.

Observation site and method

The survey was carried out in a typical tundra watershed near Tiksi, Russia (latitude 71° 38'N, longitude 128° 52'E) in the summer of 1999. The topography of this watershed consists of rolling hills, with elevations of 200-300 m, and gently sloping valleys; marshy wetlands form in the valley bottoms. Tundra polygons and frost boils are found in this area; the thickness of the permafrost is estimated to be over 500 m (Fartyshev, 1993). The ground thaws to maximum depth in August, then refreezes from early September.

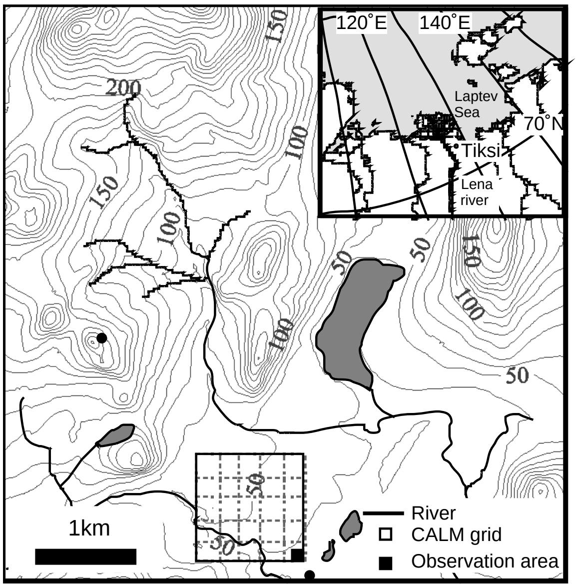

Fig. 1 Study area

Table 1 Characteristics of soil near the observation site.

Horizon type	Depth	Range	Bulk density	Range	Hydraulic cond.	Range	Thermal cond.	Range
	(cm)		(g cm^{-3})		(cm s^{-1}) (10^{-4})		(WmK^{-1})	
Live-plant	5-0	0.5-20					0.53	0.23-0.74
(moss)			0.21	-	10^4	-		
(sedge)			-	-	4.6 (root)	-		
Organic soil	0-19	7-42	0.68	0.25-1.01	61	140-4	0.88	0.70-1.21
Mineral silt	19-36	9-40	1.32	0.75-1.71	0.59	1.1-0.2	1.14	1.02-1.35
Frozen	36-	-	-	-	-	-	-	-

An area 100 × 100 m was selected at the southeast end of the CALM grid (Fig. 1). Figure 2 shows air and soil temperatures, precipitation, and groundwater level at the observation area (10-20 August, 1999). The average air temperature was 7.3 °C and the average soil temperature at a depth of 0.1 m was 7.0 °C for the period of record; there was a precipitation event larger than 10 mm/day. Parts of the area were covered by a mat of moss, forming a 0.03-0.2 m layer of live plants. The soil in the area is a multi-layered system that consists of 0-0.2 m of accumulated organic material on 0.05-0.3 m of partially decomposed organic matter, over mineral silt above the permafrost (Watanabe *et al*., 2000). Table 1 lists the physical properties of the soil in the observation area (Watanabe *et al*., 2000). The hydraulic conductivity of the organic soils was 10 to 100 times greater than that of the silt. The live-plant layer had a very high hydraulic conductivity. Thermal conductivity increased with depth from the live-plant layer through the organic soil to the silt.

The observation area was divided into a 10 m grid. At each intersection of the grid, the ground surface level, thaw depth, and groundwater level were investigated. The leveling survey was conducted from a benchmark placed the previous year. Thaw depth was measured using a steel rod, pushed vertically into the ground. After measuring thaw depth, the groundwater level was measured in each of the holes made by the steel rod. The vegetation cover in each 10 m square grid was classified by the dominant species observed.

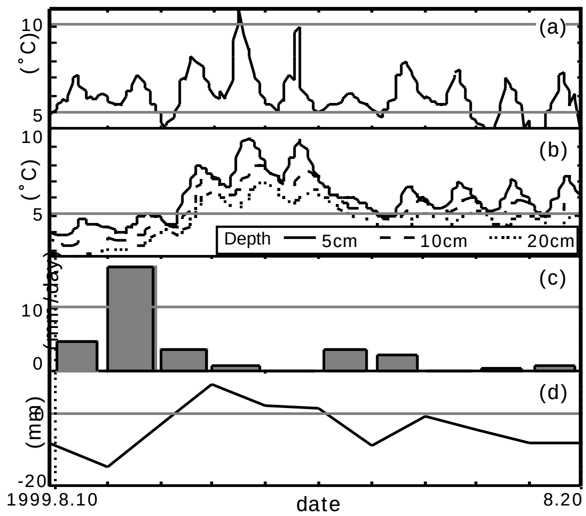

Fig. 2 Time series of the meteorological data. (a) Air temperature at 1 m high; (b) Soil temperatures at 3 depths; (c) Precipitation in a day; (d) Water level from ground surface.

Results

Ground surface level and thaw depth

Figure 3 shows a map of the ground surface level in the observation area. The ground level ranged from EL.+34.30 to EL.+35.63 m, averaging EL.+35.15 m. The ground surface sloped gently from west to east. Figure 4 shows a map of the groundwater level at the observation area before the rainfall on 12 August. The groundwater level ranged from EL. +34.31 to EL.+35.42 m and averaged EL.+35.07 m. Like the ground surface, the water table sloped from west to east. There were some small mounds in the northwestern part of the observation area; at these points, water levels were less than 0.2 m below the ground surface. On the other hand, pooled surface water not less than 0.05 m deep existed at some points on the diagonal line of the observation area (northeast-southwest) and at the southeast end of the area.

Figure 5 shows a map of thaw depths measured using the steel rod on 19 August. The average thaw depth was 0.61 m; the maximum and minimum were 1.02 and 0.29 m, respectively. The ground thawed to a deeper level in the northwestern part of the area. Some singular points were observed, at which the thaw depth was close to 1 m, around the northwesterly midpoint of the area. The level of the frozen ground table was obtained by subtracting the thaw depth from the ground surface level (Fig. 6). The frozen ground level ranged from EL.+33.78 to EL.+35.04 m, averaging EL.+34.54 m.

Vegetation cover

The vegetation in the observation area consisted mostly of water-tolerant plants, such as sedges and mosses accompanied by lichens. The vegetation cover was classified into three types: sedges dominant, mosses dominant, and mixed. Figure 7 shows a map of the vegetation, along with the thaw depth contours. The ground was mainly covered with sedge in the western part of the area, where the thaw depth was greater than 0.6 m. The soil in this area consisted of a shallow organic layer (about 0.1 m), and a silt layer that included a lot of gravel. On the other hand, mixed vegetation of moss and sedge was noticeable in the eastern part of the area, where the thaw depth was shallow. In this area, the water level was close to the ground surface and the organic layer was about 0.2 m thick. There were some patches of moss-covered ground in the southeastern part of the area, where the live-plant layer was thicker than 0.1 m and the thaw depth was especially shallow. In addition, frost boils about 0.5 m in diameter were found in the area. These frost boils supported no vegetation cover and the soil consisted of silt only. The ground

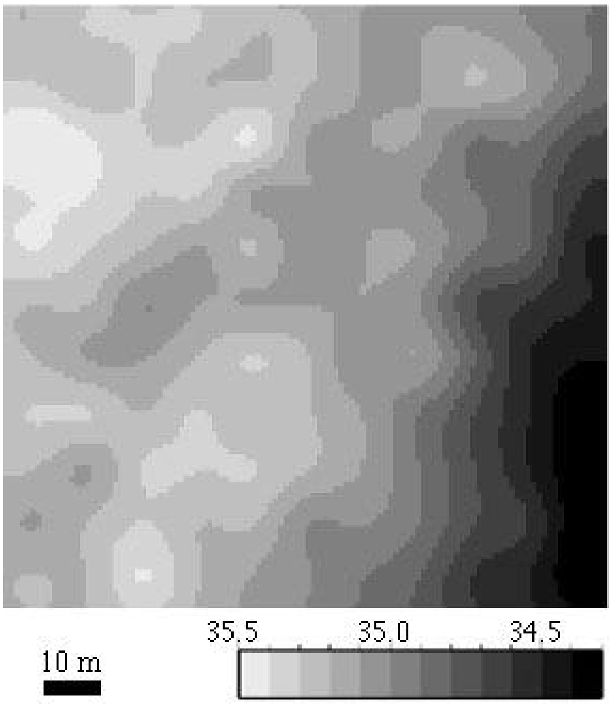

Fig. 3 Map of the ground surface level.

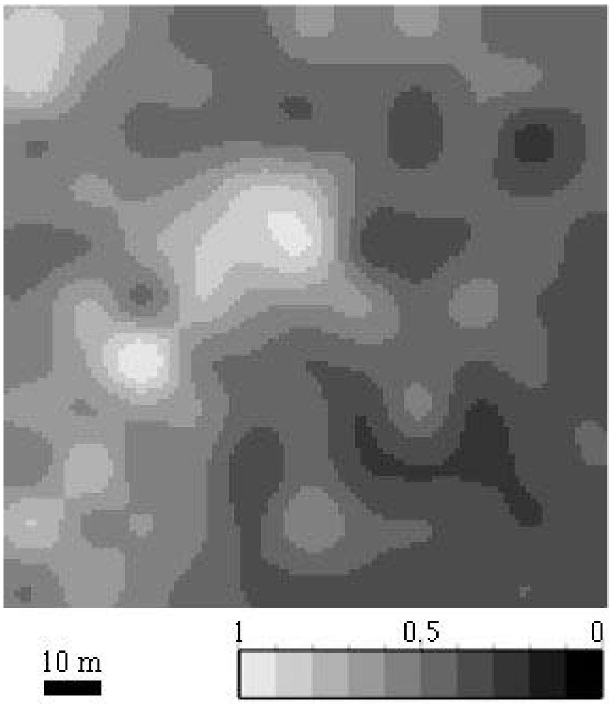

Fig. 5 Map of the thaw depth (19 August).

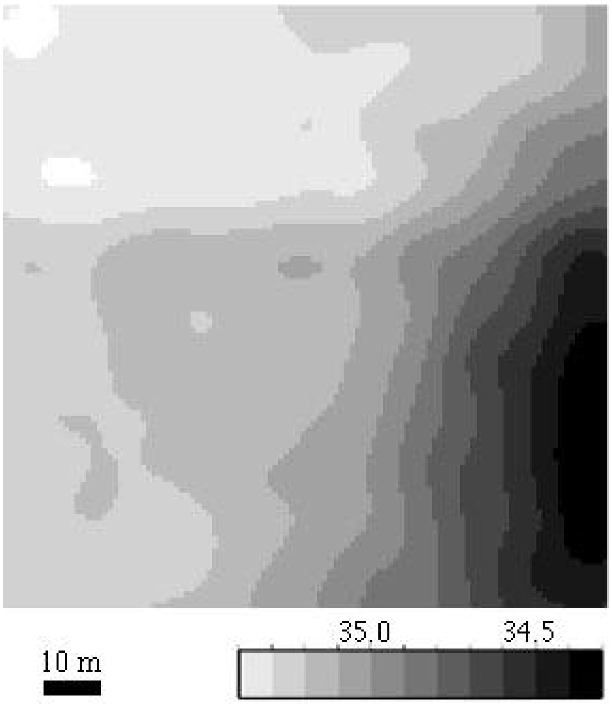

Fig. 4 Map of the ground water level (12 August).

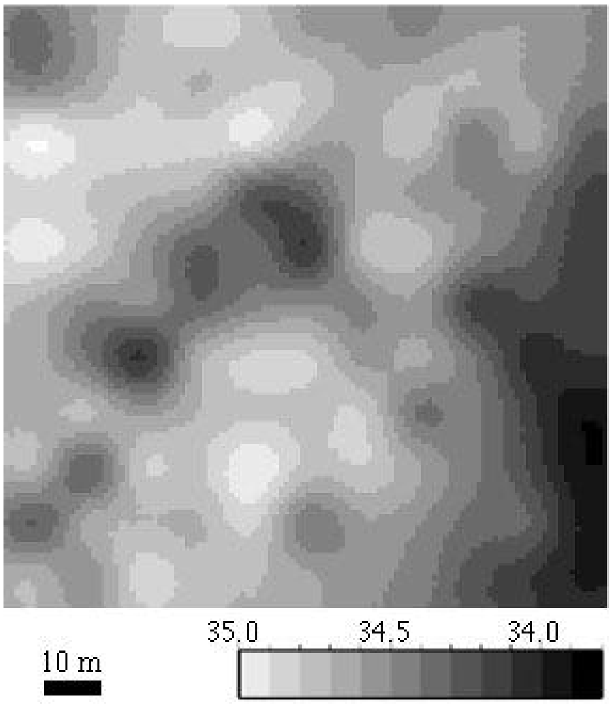

Fig 6. Map of the frozen ground level (19 August).

that was studded with frost boils thawed to a greater depth than the surrounding area.

The appearance of the vegetation varied with moisture conditions at the soil surface. Sedges were green and grew densely in ground close to saturation; sedges were yellowish or whitish and grew thinly in unsaturated ground; and a few sedges grew in the waterlogged surface. No marked difference was observed in the density of moss due to moisture conditions, but differences in color similar to those in the sedges were observed.

Discussion

The slope direction of the ground surface and the gradient were calculated from the ground surface level using GIS analyzing software (GRASS). The gradients ranged from 0 to 3°. Figure 8 shows a map of the slope direction for gradients larger than 1°, along with the thaw depth contours. The slope directions were separated into four segments (north, east, south, and west). Slopes were well scattered in the western part of the observation area, indicating that the ground was rolling. Slopes predominantly faced east in the eastern

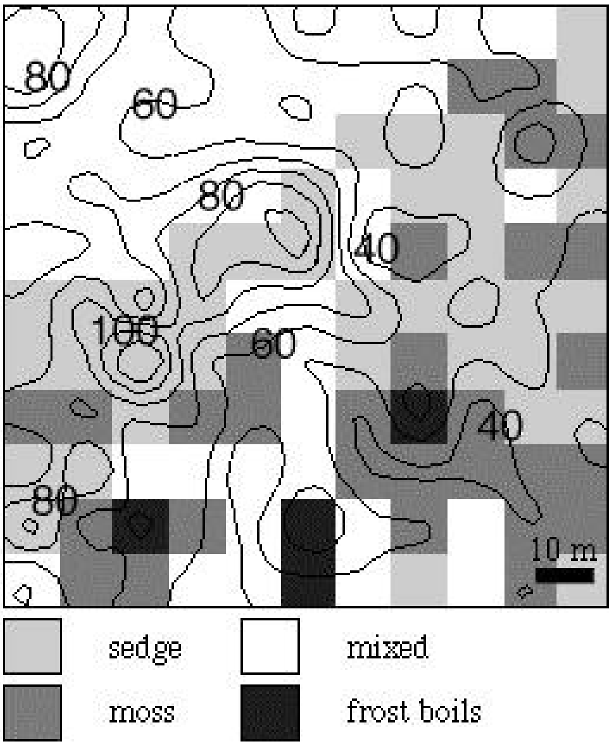

Fig. 7 Vegetation map. The solid lines are the thaw depth contour with a 0.1 m interval.

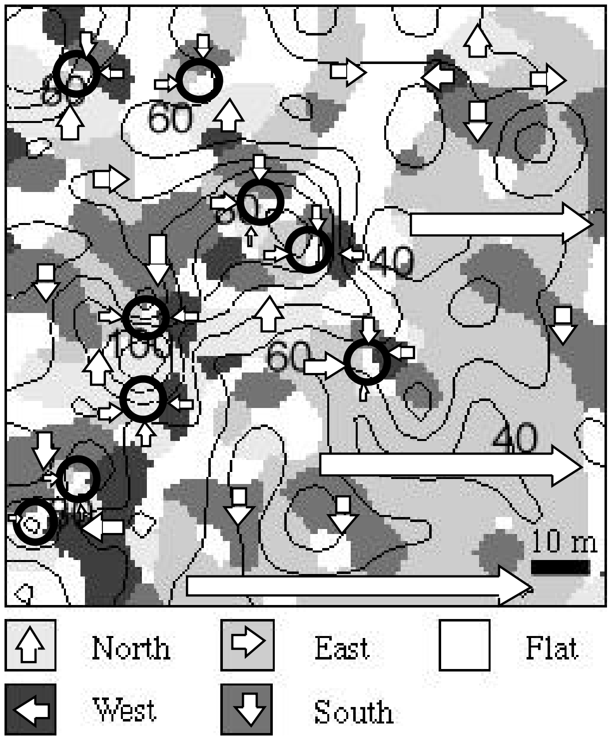

Fig. 8 Map of the slope direction for gradients lager then 1˚. The solid lines are thaw depth contour with a 0.1 m interval. The circles indicate micro-depressions.

part of the area, indicating that the ground continuously sloped in one direction. The thaw depth of the ground was less than 0.4 m in areas of continuous slope. Slopes in all four segments faced each other at some points (circles in Fig. 8), indicating that the ground formed a micro-depression with a depth of about 0.1 m. The ground thawed to a greater depth near the micro-depressions than in the surrounding areas.

The silt layer tended to remain saturated, with little temporal variation, due to the presence of permafrost below it; on the other hand, the moisture content of the organic layer fluctuated greatly over a short time. This indicates that, the water flows into, and then through, the organic layer along the slope direction (indicated as arrows in Fig. 8). If the organic layer has dried sufficiently, the outflow is delayed by rewetting of the organic layer. Referring to Fig. 2, the ground water level fluctuated between –20 and 10 mm, indicating that the micro-depressions became filled with water during the survey period. In the initial period of ground thawing, water tended to flow into the micro-depressions and form puddles before runoff occurred. When this happens, heat advection by the water flow will accelerate thawing of the ground in the micro-depressions. Meanwhile, the ground surface in this area repeatedly freezes and thaws several times in May. The heat capacity of the standing water in the micro-depressions will prevent the ground from refreezing.

In the moss-covered areas, shallow thaw depths were observed. Since the moss covered the ground surface densely and formed a thicker live-plant layer than other plants, thawing was prevented in moss-covered areas. A thick organic layer was observed in the area where mixed vegetation of moss and sedge covered the ground. The organic layer had much less thermal conductivity than silt and insulated the silty layer. Thus, the silt layer remained cool during the ground thawing period. Frost boils, near which the ground thawed deeper than in the surrounding area, consisted of silt with a high thermal conductivity, and their surface had no vegetation and a low albedo. Consequently, thawing proceeded faster near the frost boils. The variation in the thaw depth in August may reflect the thawing processes.

Conclusion

To understand the spatial variation of thaw depth in a tundra watershed and its relationship with surface conditions, ground surface level, thaw depth, and vegetation cover were investigated in the summer of 1999 near Tiksi, Siberia. The thaw depth varied spatially within a range of 0.3 to 1 m throughout the 100 × 100-m observation area. Surface micro-undulations were observed in the area, and their distribution was surveyed. The differences in micro-undulation and vegetation cover influenced the spatial variation of thaw depth.

The thaw depth of a tundra watershed varies spatially and temporally. Although this variation is important in understanding hydrologic interactions, it is difficult to identify the variation in a large watershed in a short time. This study showed that thaw depth is closely related to micro-undulations and surface conditions, such as the species, color, and density of vegetation. If surface information can be obtained from photographs and combined with information about micro-topography, the spatial variation of thaw depth can be geographically predicted. Knowledge of these characteristics is vital for hydrologic modeling of tundra watersheds.

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