Polar Meteorol. Glaciol., **15**, 78–90, 2001

Characteristics of the water cycle in the discontinuous permafrost region in interior Alaska

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Abstract: In order to better understand the water cycle in the discontinuous permafrost area, field observations of soil moisture content, groundwater table, discharge and evaporation have been carried out in the Caribou-Poker Creeks Research Watershed since 1997. This investigation aims to characterize the soil moisture and ground water dynamics of interior Alaska. Soil moisture content depends on topographic factors, increasing toward the bottom of a slope. In the flood plain, soil moisture is higher in depressions than on mounds. The depth of the active layer is less than 1 m at the end of summer and unfrozen soil exists below the permafrost, as determined through geophysical exploration and drilling. The groundwater table reaches a maximum height in early October and decreases monotonically to reach a minimum in early April, then starts to increase after snowmelt. The ground water of a shallow well and soil moisture near the ground surface show variations, as influenced by precipitation and evaporation; however, a deeper well on the upper slope does not respond similarly. Evaporation occurs over the whole watershed during summer; however, directly over a stream condensation dominates because of low water temperature due to the permafrost underneath.

1. Introduction

It is important to understand the hydrological cycles of high latitudes in order to establish the role of the Arctic energy and water system on the global climatic process. The hydrological cycle is composed of various factors such as precipitation, snowmelt, evaporation, soil moisture, ground water and discharge. However, the vertical water flux across the frozen soil is highly variable depending on surface and subsurface conditions and is generally unknown in interior Alaska. Soil moisture represents an important parameter affecting processes such as evapotranspiration, recharge and surface runoff. Gieck and Kane (1986) reported that most groundwater recharge occurs during snowmelt in spite of low infiltration rates into frozen ground. Hinzman *et al.* (1997) showed that in this area the summer precipitation just met evaporative demand and did not yield a significant contribution to groundwater recharge. Weller and Holmgren (1974), Ohmura (1982), Amiro and Wuschke (1987) and Kane *et al.* (1990) reported that evapotranspiration from the vegetated surface was the primary factor in water loss from the watershed. The summer evapotranspiration sometimes exceeds available precipitation in northern Alaska (Yoshimoto *et al.*, 1996). However, the process of infiltration of surface water to the groundwater or the response of soil moisture content and groundwater table to precipitation and evaporation represents a major unknown, and the watershed is composed of various materials, such as soil, vegetation, stagnant water in wetlands, and running water in streams. Therefore, it is important to know evaporation characteristics of the different surface conditions in order to estimate water loss from the watershed. This investigation aims to understand 1) the dependence of soil moisture content and soil temperature with surface conditions such as vegetation and topography, 2) seasonal variations of the groundwater table and 3) rates of evaporation from various surfaces of the experimental watershed in summer.

2. Observation site and instrumentation

Observation sites were established in the Caribou Poker Creeks Research Watershed (CPCRW), which is a headwater basin located 50 km north of Fairbanks at 65.19°N, 147.5°W (Fig. 1). The CPCRW has been one of the most investigated watersheds in

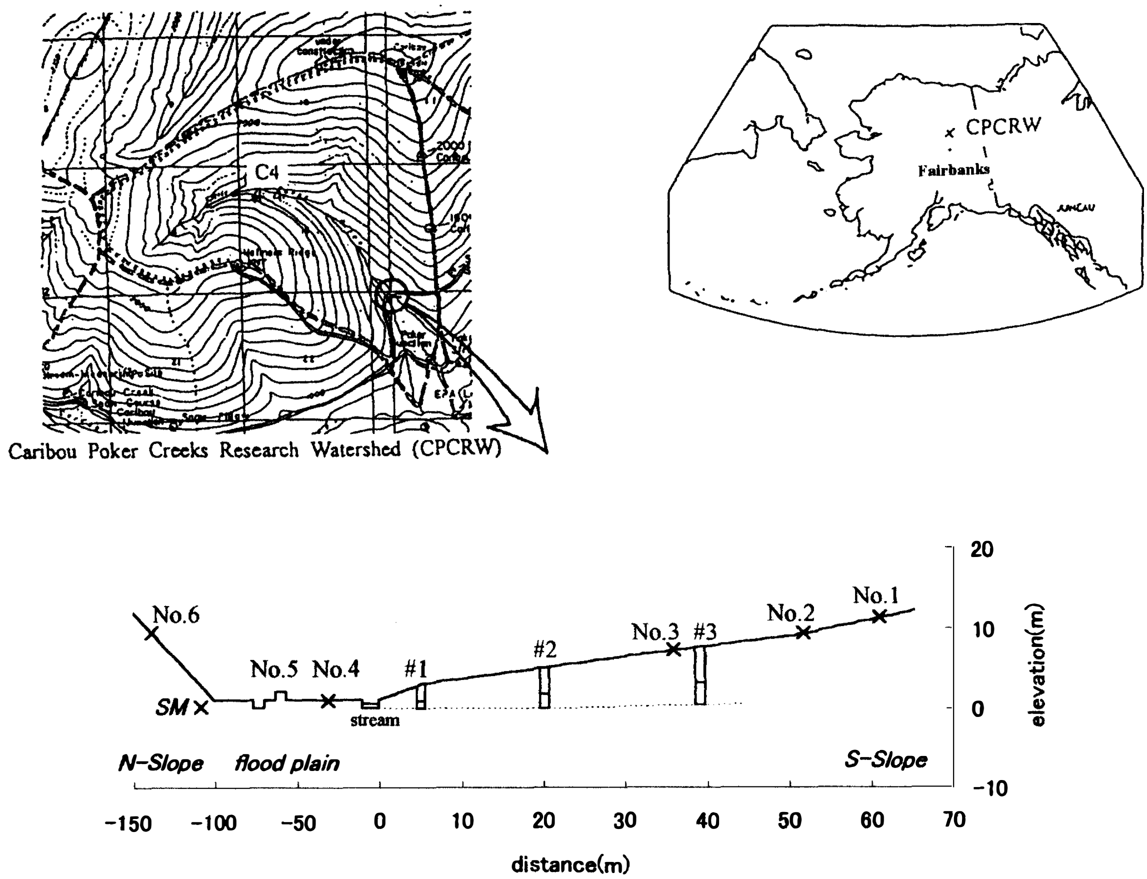

Fig. 1. Descriptions of CPCRW.
No. 1~No. 6: observation sites for soil temperature and moisture content at open and forested areas. #1~#3: well sites, SM: observation site of soil moisture monitoring.

high latitudes since 1969. The topography and climate of the CPCRW are described by Koutz and Slaughter (1972) and Lotspeich *et al.* (1976). Sub-drainage C4, with an area of 11 km^2, was chosen for detailed observations of soil moisture content and ground water height (Fig. 1). Vegetation of C4 is dense birch forest on south-facing slopes, black spruce on north-facing slopes, and tussocks, willow bushes and moss in the flood plain. Firebreak about 30 m wide runs from the top of the slope to the valley bottom, where vegetation is almost the same as in the flood plain. The area of the firebreak is called an open area in this paper. Meteorological and hydrological observations such as air, soil and water temperatures, wind speed, solar radiation, humidity, soil moisture content and runoff have been conducted for three years (1997 to 2000). Three wells were drilled in the open area along a south-facing slope (#1~ #3 in the figure) in 1997. After drilling, a plastic pipe riser (PVC threaded pipe) with 5 cm diameter was inserted as a casing, which equipped 0.6 m long strainer (screen) with 0.25 mm mesh size and 0.4 m long bottom cap at the bottom end. The ground water height was recorded by using a pressure transducer. SM in the figure is the site for measuring soil moisture content. Sensors were set in three different layers: moss, organic and mineral soil. Soil moisture (volumetric water content) was measured using a frequency domain reflectometer (FDR). Furthermore, the intensive measurement of volumetric water content and soil temperature of the upper part of the surface layer were carried out in snow-free seasons from 1998 to 2000 along the south-facing slope and a portion of the valley floor (Fig. 1). The observation sites were set in open and forest areas at the same elevation, close to each other (20–30 m apart). Measurements were made 4 or 5 times a day except on rainy days. Evaporation from the water surface was measured directly with an evaporation pan. The instrumentation is listed in Table 1.

Table 1. Observation items and methods.

Items	Instrumentation
(Continuous measurement)	
Air temperature	Thermistors in radiation shelter
Surface temperature	Thermistor and infrared thermometer
Relative humidity	Polymer hygrometer
Wind velocity	Three cup anemometer
Solar radiation	Pyranometer
Net radiation	Net radiometer
Soil & water temperature	Thermistor thermometer
Water level of well	Pressure transducer
Soil moisture content	Frequency domain reflectometer
(Manual measurement)	
Evaporation	Evaporation pan
Temperature & humidity	Assmann psycrometer
Surface albedo	Albedo meter
Soil moisture content	Frequency domain reflectometer
Soil temperature	Thermistors thermometer

3. Observation results

3.1. Soil temperature and soil moisture

The depth of the active layer was variable depending on surface vegetation, hillslope aspect and micro-undulation, but the maximum depth was less than 1 m at the end of summer. The underground structure was obtained by geophysical exploration and confirmed by well borings at three different points along the slope. Figure 2 is the electric resistivity profile under the south-facing slope. Resistivity of the frozen soil or

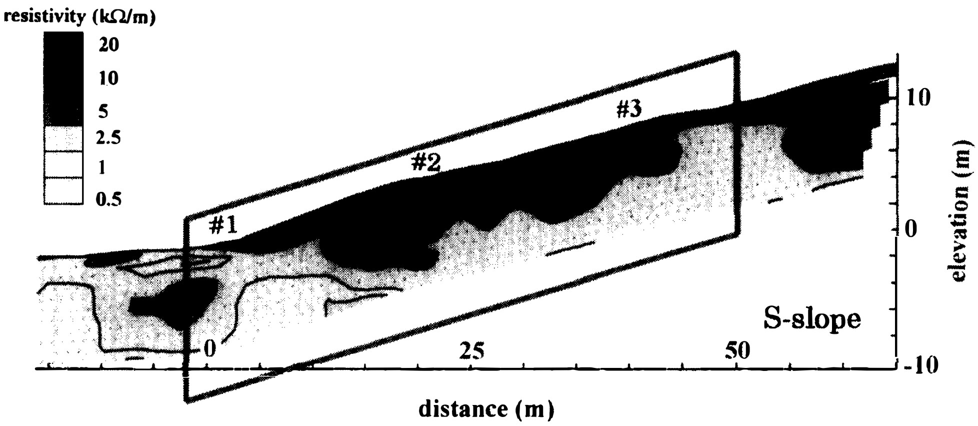

Fig. 2. Resistivity profile under the south-facing slope. Shades show the degree of the electric resistivity.

schist rocks is high, so the figure shows the existence of frozen soil with several m thickness just below the ground surface and an unfrozen zone under the frozen soil. Extensive measurements of soil temperature and soil moisture content were carried out at fixed specific points in the watershed (No. 1 to No. 6 in Fig. 1). Figures 3a and b represent the extremes and mean soil temperatures at 10 cm depth at open sites (a) and forested sites (b), respectively. These were obtained by using only values around noontime in early June for three years because that was a relatively low precipitation season in interior Alaska. Numbers along the abscissa represent sites: No. 1 to No. 3 are on the south-facing slope, No. 4 is near the stream, ⊔ and ⊓ are sites of depression (concave) and mound (convex) on the flood plain, and No. 6 is on a north-facing slope with the same elevation as No. 2. The temperature ranges are wide on the upper slope, especially at open sites. The soil temperature decreases toward the bottom of the slope; this tendency is pronounced in the open area. Soil temperature at the forest site is lower than that at an open site at the same elevation and same aspect of the slope. Also the temperature in the depression is lower than that on the mound.

Figures 4a and b show the volumetric water content in the layer 15 cm below the surface at open and forest sites, respectively. The soil moisture at the open site increases toward the bottom of the slope; at the flood plain it becomes larger in the depression than on the mound. The soil temperature and moisture content at the open site show the same dependence on topographic factors such as elevation, vegetation and micro-undulation. However, such a trend is not clear at the forest sites. The relationships between soil temperature and soil moisture content of the open and the forest sites

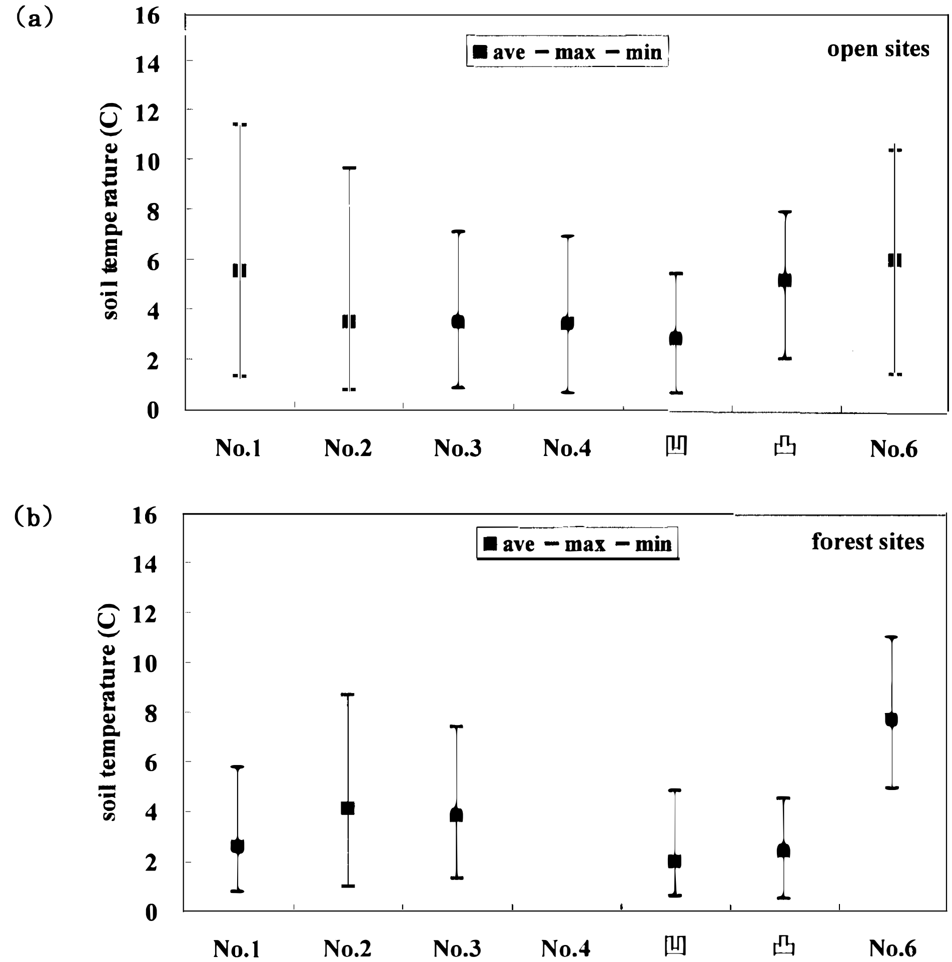

Fig. 3. Soil temperatures at 10cm depth for three summer seasons. (a) open sites. (b) forest sites.

on the south-facing slope are displayed in Figs. 5a, b. The variability is large, but a regressive relationship is seen at the open site on the south-facing slope, namely; the soil temperature decreases with increasing soil moisture. However, the relationship is not clear at the forested sites. In this observation the soil temperature and soil moisture in the shallow surface layer vary from place to place even in a small area. Soil temperature is more commonly measured than soil moisture. If there is a relationship between the both factors, the soil moisture content might be estimated by using the soil temperature. Therefore, all values are compared with the values of the reference point (site No. 2). Figures 6a, b show the relations among the normalized soil temperature and the normalized soil moisture. In this paper the normalized temperature means the temperature ratio to site No. 2. Along the south-facing slope and flood plain, normalized temperature decreases with increasing soil moisture. This means that when the soil moisture at any site is larger than at No. 2, the soil temperatures at that site are lower than at No. 2. This may suggest that once we have the soil temperature and soil moisture at a specific point on a south-facing slope, we can estimate the soil moisture at

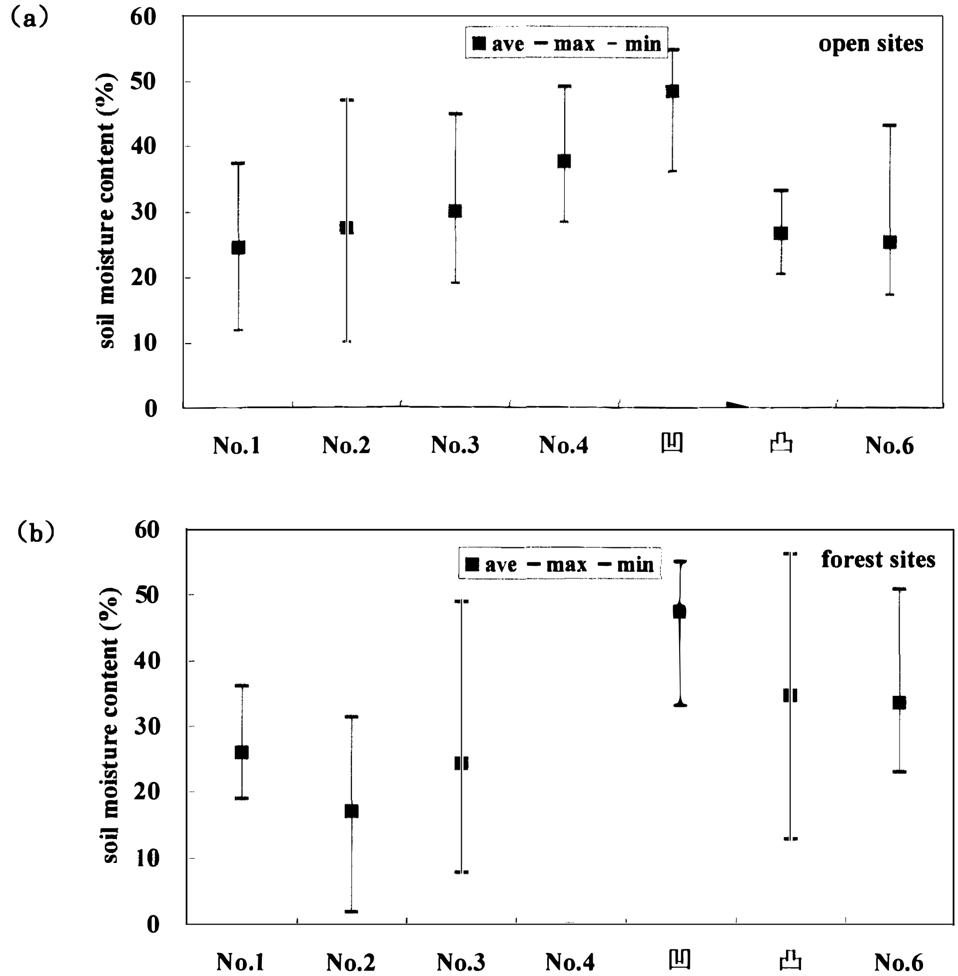

Fig. 4. Same as Fig. 3, but volumetric water contents.
(a) open sites. (b) forest sites.

any point using the soil temperature at that point. On the north-facing slope, at the same elevation as No. 2, the soil temperature is much lower than at No. 2 even though the soil moisture content is the same. On the other hand, such a tendency is not seen at the forest sites (Fig. 6b), namely; soil temperature does not change along the slope or flood plain even though soil moisture changes widely.

3.2. Groundwater

Three wells were drilled along the south-facing slope for groundwater level measurement. The well depths are 2.5 m (#1), 5.0 m (#2) and 6.5 m (#3), at which depth the boring machine stopped working, suggesting the presence of bedrock. The soil structure at the drilling area is as follow: at wells #2 and #3 the upper layer was unfrozen soil (active layer) with several tenth cm, the next was a frozen soil layer with 2–3 m depth and the unfrozen soil appeared below that. On the other hand, no frozen soil was found at well #1. Figure 7 shows the groundwater table of well #3 from August 1997 to May 1999. The groundwater table reaches the maximum height in early October.

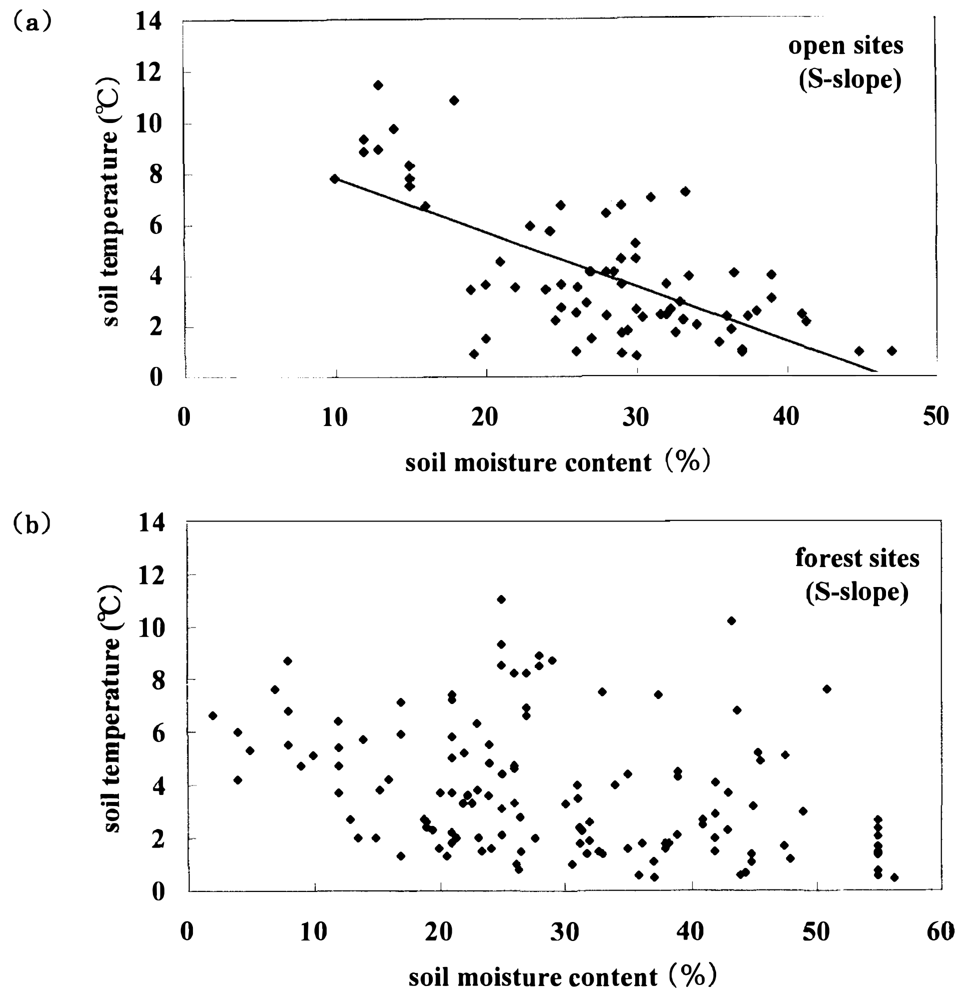

Fig. 5. Relationships between soil temperature and soil moisture of a south-facing Slope. (a) open sites. (b) forest sites.

During the winter it decreases gradually, reaches the minimum in early April, and starts to increase after snowmelt. The variations of the water table of two wells (#1 and #3) are compared with precipitation in summer of 1998 (Figs. 8a, b, c). The date missing from 27 June to 8 July was due to water sampling for chemical analysis. The groundwater table of well #1 shows a large variation, which is due to precipitation. It also shows a small diurnal fluctuation with the magnitude of 1–2 mm/day. However, the water table of well #3 (deeper well) never shows such a fluctuation.

3.3. Evaporation

The stream discharge near well #1 displays the same ground-water dynamics as the shallow well, namely; large variation due to precipitation and small diurnal fluctuation (Fig. 9). Such small diurnal variations appeared in soil moisture, too. So it is considered that evaporation from a water surface or a vegetated soil surface might influence it. The daily evaporation rate from the wetland water surface was obtained by the measurement of water level change of an evaporation pan, and evaporation rates

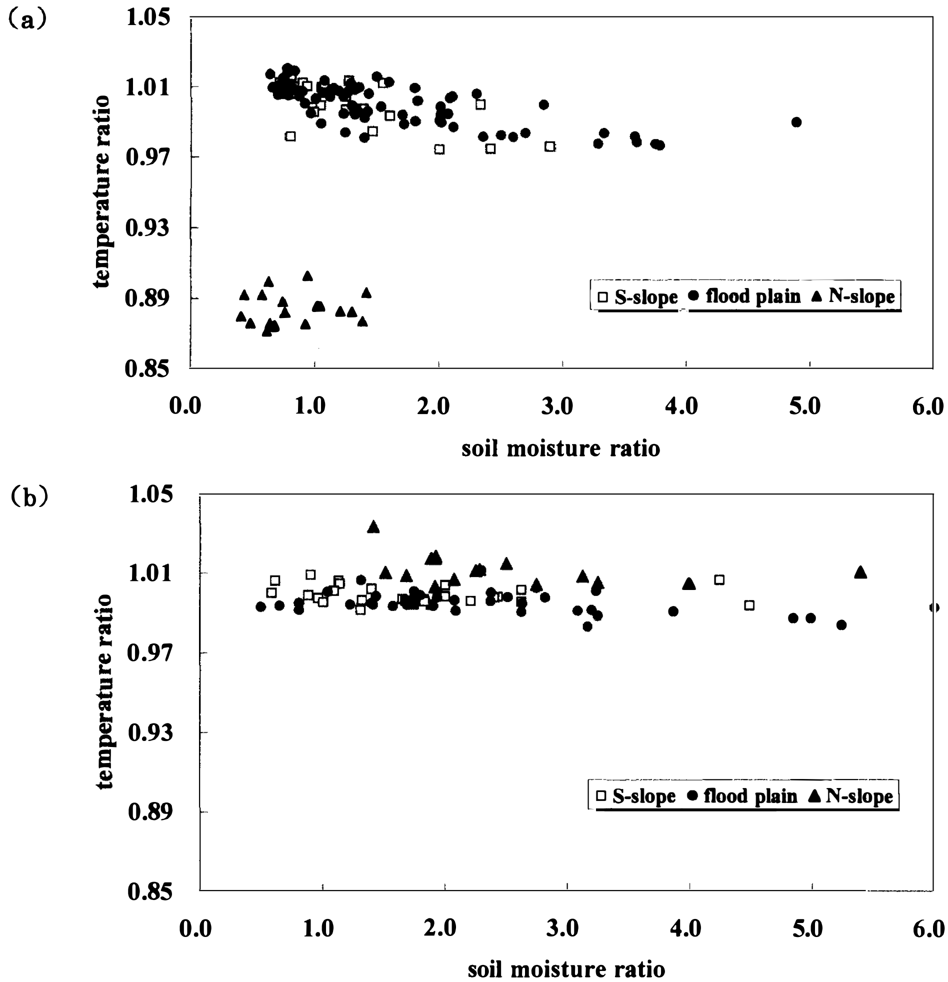

Fig. 6. Relations between normalized soil temperature and normalized soil moisture. (a) open sites. (b) forest sites.

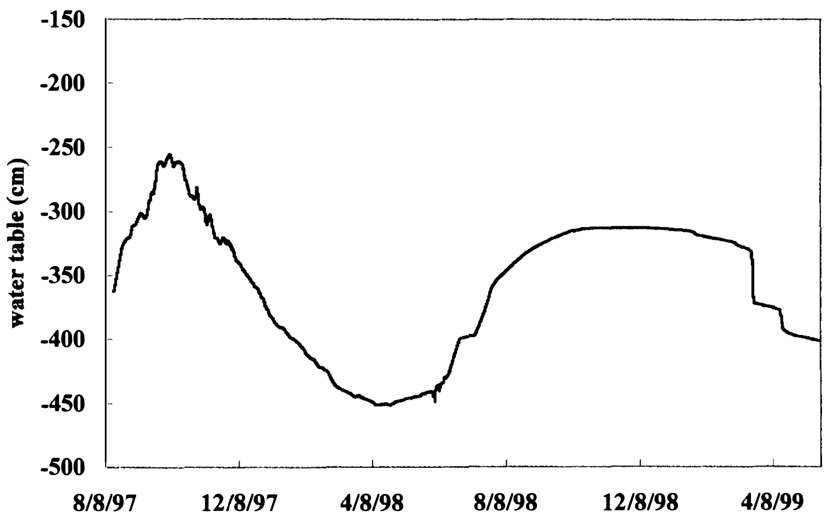

Fig. 7. Variation of groundwater table of well #3 for two years.

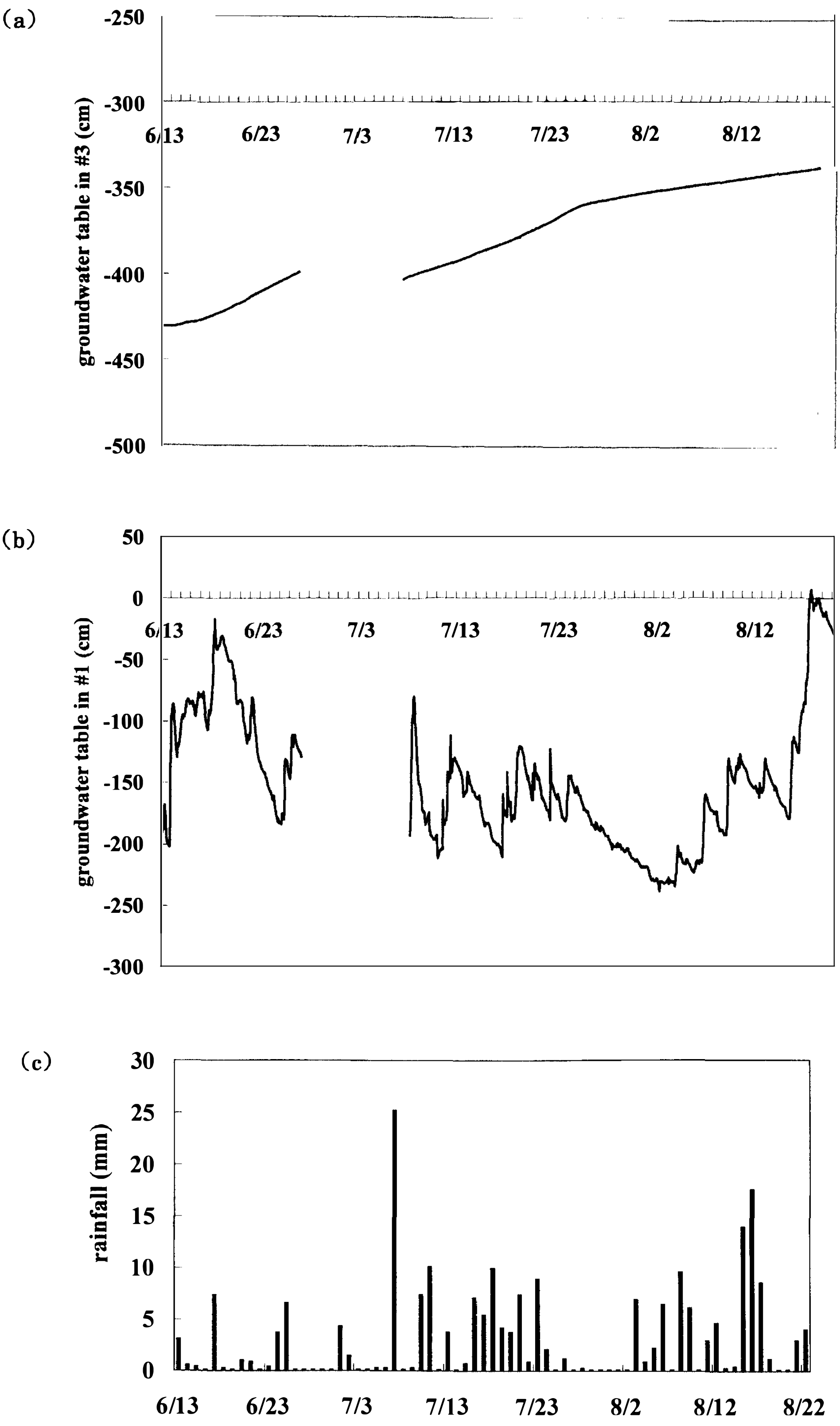

Fig. 8. The change of groundwater table and daily precipitation in the summer of 1998. (a) well #3. (b) well #1. (c) precipitation.

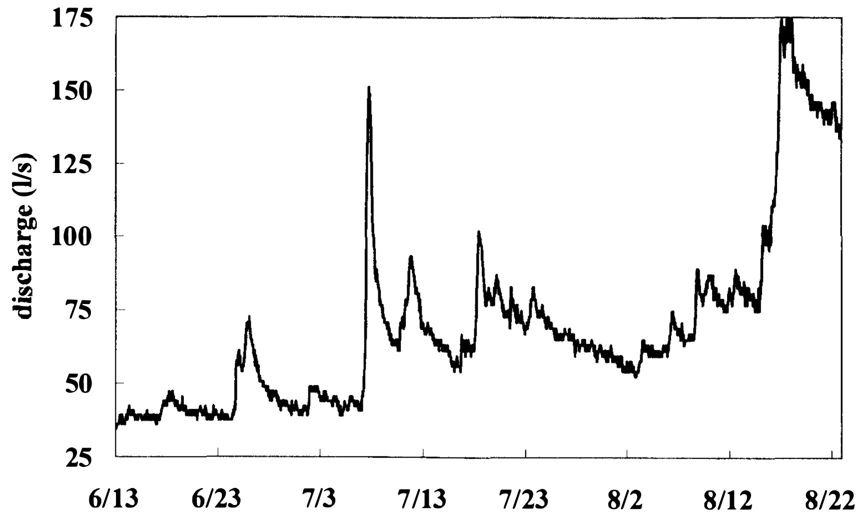

Fig. 9. Discharge of a stream in the summer of 1998.

from various surfaces were evaluated by the aerodynamic method,

$$E = 0.622 \rho h V (e_a - e_o)(P)^{-1}, \tag{1}$$

where ρ is the air density (kgm^{-3}), h the transfer coefficient for water vapor (dimensionless), V the wind velocity (ms^{-1}), P the atmospheric pressure (hPa), e_a and e_o the water vapor pressure in the air and on the surface (hPa). We adopted the value of 4.03×10^{-3} as the transfer coefficient, which was obtained by Ishikawa *et al.* (1988) at the Glenn Creek Watershed near the CPCRW in summer. The mean air temperature of the two weeks observation in June 1999 was 12.3°C and the maximum daily range was 19°C. The mean temperature of the vegetated soil surface was slightly higher than that of the air, and the water temperature of an evaporation pan, in which the water was stagnant, was almost the same temperature as the air, but the daily range was smaller. The stream, which was running water, maintained very low temperatures (the mean was 4.1°C) and had a small daily range even in summer. Figure 10 shows the difference of water vapor pressures between the air and various surfaces (stagnant water, stream, vegetated soil surface) for a short period in summer of 1999. The water vapor pressure at the soil surface partly covered by vegetation is assumed to be the saturated vapor pressure. Water vapor pressures at the surface of soil and stagnant water are much larger than that in the air, but the reverse is true at the stream surface because of low water temperature. Evaporation rates from the various surfaces are compared in Fig. 11. The solid line on the figure represents the evaporation amount from the stagnant water surface measured directly by evaporation pan. An evaporation pan provides an estimate of the potential evaporation rather than the actual evaporation. It compares well with the calculated evaporation from eq. (1). Therefore, the coefficient seems to be reasonable. The evaporation rates from the various surfaces vary greatly. The largest evaporation was obtained at the vegetated soil surface; however, the evaporation rate from the surface is not the actual evaporation but the potential evaporation because the vapor pressure at the surface is assumed to be the saturated pressure in this calculation. From the stagnant water surface, an almost constant evaporation rate (2–4

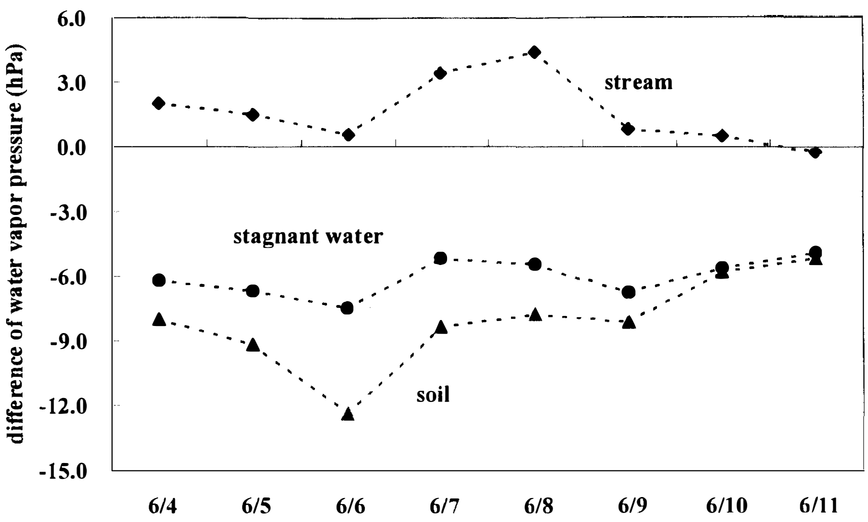

Fig. 10. Differences of water vapor pressure among the air and various surfaces (vegetated soil surface, stagnant water, stream).

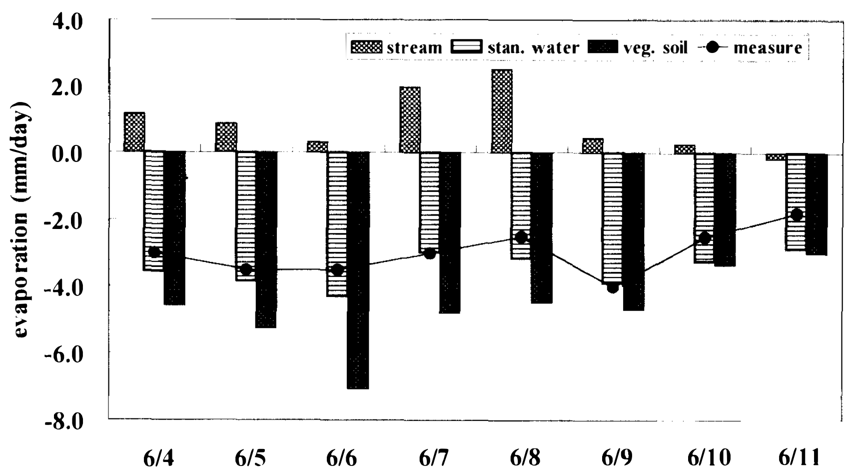

Fig. 11. Comparison of evaporation on various surfaces (vegetated soil surface, stagnant water and stream).

mm/day) is obtained. On the other hand a certain amount of condensation occurs on the stream surface (0.3–2.5 mm/day), which is caused by the low stream temperature due to the presence of frozen soil. The actual vapor pressure at the vegetated soil surface might be obtained by measurement of soil moisture content and knowledge of the soil characteristic curve (Hinzman *et al.*, 1998). Most of the experimental watershed is covered by moss, which is porous material, so direct measurement of the relative humidity of the moss layer was attempted for evaluating the actual evaporation. A humidity sensor covered with a high-tech material that passed the water vapor but repelled liquid water was inserted just below the moss surface. Figure 12 shows the evaporation ratio (actual evaporation/potential evaporation) from the moss surface at the depression and mound sites. A large difference is seen between the two sites: at the

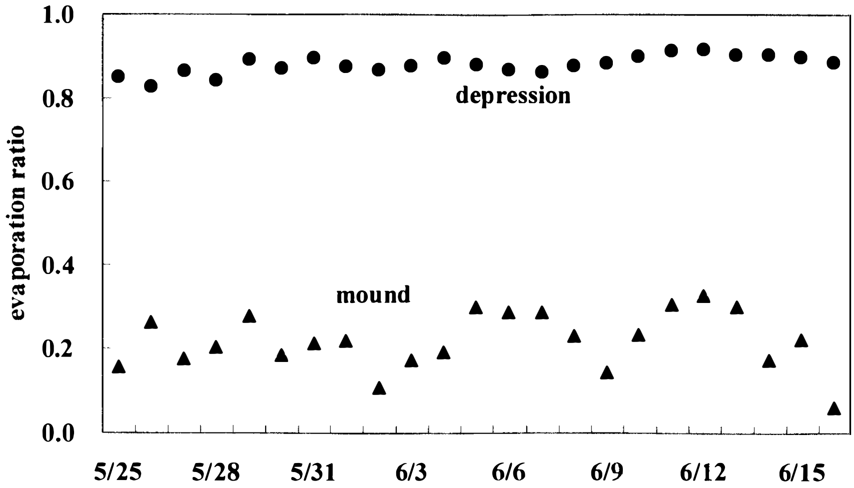

Fig. 12. Ratios of the actual evaporation to the potential evaporation on the moss surface at depression and mound sites.

former site the ratio is large, which means that the evaporation is nearly the maximum, but at the latter site, it is small, about 20 to 40% of the potential evaporation. This result suggests that the most of the water loss could be due to evaporation, which induces diurnal variations of soil moisture and groundwater table.

4. Conclusions

Observations of vertical water flux across the frozen soil, such as soil moisture, ground-water table and evaporation have been carried out at the Caribou Poker Creeks Research Watershed, interior Alaska since 1997 in order to understand the characteristics of the water cycle in the discontinuous permafrost area. Soil moisture content shows some dependencies on slope and micro-topography, such as increasing toward the bottom of the slope and increasing in depressions as compared to mounds of the flood plain. Soil moisture near the surface shows a diurnal fluctuation. The depth of the active layer is less than 1 m at the end of summer. An unfrozen layer exists below the frozen soil; its depth was obtained by geophysical exploration. The groundwater table has been measured using three wells and shows a maximum height in early October, decreasing during winter, reaching a minimum in early April, and increasing again after snowmelt. The groundwater of a shallow well shows daily fluctuation, which is influenced by precipitation and evaporation, but not at a deeper well. Evaporation with the magnitude of 2 to 4 mm/day is obtained in the watershed during summer except directly over the stream, where condensation seems to dominate, probably because of the low water temperature due to the permafrost.

Acknowledgments

The authors are indebted to Mr. W.R. Bolton, Water and Environmental Research Center, University of Alaska, and A. Takizawa, Institute of Low Temperature Science, Hokkaido University for their support of field observations. We appreciate Dr. S.

Ferguson, USDA-Forest Service, Pacific Northwest Research Station, who showed us the method of moss humidity measurement and their data.

This research was supported by scientific research grants from the Japan Marine Science & Technology Center, the Ministry of Education, Science, Sports and Culture of Japan, and the U.S. National Science Foundation Long Term Ecological Research Program.

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(Received February 21, 2001; Revised manuscript accepted August 24, 2001)