NATURAL GROUND TEMPERATURES IN UPLAND BEDROCK TERRAIN, INTERIOR ALASKA

C.M. Collins[1], R.K. Haugen[2] and R.A. Kreig[3]

[1]U.S. Army Cold Regions Research and Engineering Laboratory, Fairbanks, Alaska
[2]U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
[3]R.A. Kreig & Associates, Inc., Anchorage, Alaska

SYNOPSIS Surface and subsurface ground temperature measurements were made in drill holes representing a variety of permafrost/non-permafrost, slope exposure, elevation, vegetation, and soil conditions within the upland taiga of interior Alaska. Algorithms representing equivalent latitude and air temperature/elevation relationships are developed to more precisely define permafrost/non-permafrost boundaries within this complex terrain.

INTRODUCTION

In the discontinuous permafrost region of interior Alaska, the occurrence of permafrost is controlled by a complex of environmental and topographic factors. These site factors include landform, soils, vegetation community, slope, and aspect, as well as winter snow cover and the mean annual air temperature (Brown and Péwé, 1973; Brown, 1978; Lunardini, 1981; Nelson and Outcalt, 1983). Ground temperature data and related environmental information on the spatial relationships of discontinuous permafrost in the upland bedrock terrain of Alaska are scarce. Indirect methods of permafrost mapping, such as the use of remote sensing, are becoming more reliable with the development of geographic information systems modeling techniques (e.g. Morrissey et al., 1986). But this approach requires ground truth from actual drill hole measurements and/or surface and subsurface temperature measurements for accurate interpretation of terrain/vegetation associations related to permafrost distribution. To better understand the interrelationships among these factors and to provide the needed data, a series of thermistor cables were installed in drill holes on natural, undisturbed sites within the Caribou-Poker Creeks Research Watershed (Fig. 1).

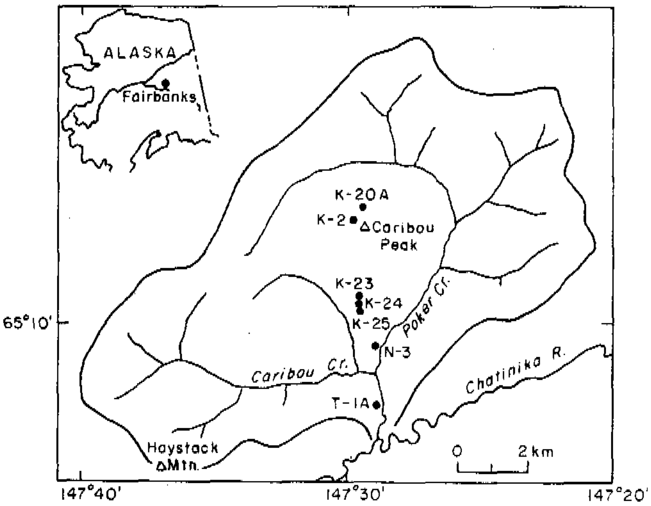

Fig. 1. Site locations in Caribou-Poker Creeks Research Watershed.

The instrumentation approach employed in this study is unique because it permits comparison of non-permafrost and permafrost surface and subsurface temperature regimes in close geographic proximity, but with different slope, aspect, elevation, and vegetative cover. The resulting data and analysis provide needed documentation and algorithms for a more accurate delineation of permafrost boundaries.

SITE DESCRIPTION

Physical setting

The Caribou-Poker Creeks Research Watershed is located within the Yukon-Tanana Uplands of central Alaska, 48 km north of Fairbanks (Fig. 1). This portion of the Uplands was not glaciated during the Pleistocene and consists of rounded, even-topped ridges and hills with gentle side slopes (Wahrhaftig, 1965). Caribou and Poker creeks are in generally flat, alluvial-floored valleys that are up to 400 m wide. Elevations in the watershed range from approximately 195 m at the mouth of Poker Creek to 826 m on the ridge at the far northern edge of the watershed. Caribou Peak, at 773 m, is a prominent peak in the center of the watershed.

Climate

Interior Alaska is a region of pronounced continental climate characterized by large diurnal and annual temperature variations, low annual precipitation, low cloudiness, and low humidity. Primarily because of its higher elevation, most of the watershed is warmer in winter and cooler in summer than Fairbanks. Mean annual air temperatures within the watershed range from -4.9°C at the valley bottom to -2.9°C on Caribou

Peak, with the highest temperature of -1.2°C at sites on the south-facing side of Caribou Peak, at intermediate elevations between the valley bottom and the peak (Haugen et al., 1982). Within the watershed the greatest temperature contrasts are in winter, when the valley bottoms are beneath the regional air temperature inversion and are quite cold compared to the higher sites above the inversion (Bilello, 1974; Haugen and Brown, 1978).

Geology and soils

The Caribou-Poker Creeks Research Watershed is underlain by rock of the Yukon-Tanana Terrane, an igneous and metamorphic complex that extends more than 1000 km from east-central Alaska to the southern Yukon Territory (Foster et al., 1973). Within the watershed itself, the underlying rocks are quartz-mica schists, garnet-mica schists, and micaceous quartzites of the green schist facies (Forbes and Weber, 1982), with quartz-mica schist predominating. The rock is deeply weathered to >20 m.

Colluvium derived from the underlying weathered bedrock is found on the flanks of the hills and on valley slopes. The colluvium probably includes some inactive solifluction deposits. Soil creep is an important ongoing process along the north-facing valley slopes of the watershed (Wu, 1984). A thin cap of loess mantles the area, but because the loess is derived from the floodplains of streams draining areas of the same rock type, there is no sharp boundary between the loess and colluvium derived from the weathered schist below it (Rieger et al., 1972). Much of the loess that was present on the slopes has been retransported to the valley bottoms, with retransported silt fans and aprons occurring along the valley sides. These silt deposits are frozen and contain ice-rich sediments and organics (Péwé, 1982).

Soils in the watershed are generally thin, poorly developed silt loams that contain varying amounts of sand or angular gravel, which is derived from weathered bedrock within a meter or so of the surface. Rieger et al. (1972) mapped seven soil series within the watershed; they can generally be divided into permafrost-underlain soils, which are poorly drained, and permafrost-free soils. Permafrost-underlain soil series as mapped comprise 30% of the watershed. Detailed soils information based on the drill logs is available (Collins and Zenk, in prep.).

Vegetation

The vegetation of the watershed is characteristic of the interior Alaska upland boreal forest (taiga), with black spruce growing on north-facing slopes and in poorly drained valley bottoms. Aspen, birch, alder, and white spruce are found on well-drained soils, typically located on south-facing slopes. Variations in vegetation communities over short distances are caused by variations in slope, aspect, drainage, post-fire successional stage, and geomorphic processes.

A large wildfire burned over most of the watershed about 1910. The varying intensity of the fire in different areas of the watershed has apparently affected the rate of succession, the distribution of plant species, and the composition of the vegetation communities now found in the watershed (Jorgenson et al., in press).

METHODS

Instrumentation

The seven instrumented sites are located along a south-to-north transect and form an almost complete topographic profile of the watershed (Fig. 1). The profile starts on a frozen northeasterly facing low-angle slope near the valley bottom of Poker Creek. It then ascends the unfrozen south-facing slope of Caribou Peak. The profile extends over the top of Caribou Peak and ends on the frozen north-facing slope.

Instrumentation consists of cables with 10-16 thermistors spaced along the length. Cable lengths range from 4.3 to 12.3 m depending on the depth of the original borehole. Drilling was done in the winter, and great care was taken during drilling to minimize disturbance of the natural ground cover and to clean up all drill cuttings. After drilling, the multipoint thermistor cables were installed in PVC pipe filled with silicon fluid to minimize convection (Osterkamp, 1974). The cables were equipped with long readout extensions so that foot traffic was not necessary in the vicinity of the thermistor installation. Thermistor resistance measurements were made weekly using a digital multimeter.

Site descriptions

Site characteristics, including drill hole depth, setting, slope, and aspect, are listed in Table 1. Site T-1A is located in the valley of lower Poker Creek, approximately one kilometer downstream from the junction of Caribou and Poker creeks. Site T-1A is typical of a continuously frozen retransported silt fan, commonly found in valleys of interior Alaska. The vegetation varies from stands of open black spruce (Picea mariana) forest (canopy 25-60%) to a black spruce woodland complex (canopy 10-25%). The ground cover consists of a 45-cm-thick organic mat of feather mosses and lichens. The entire 10.4-m hole is in frozen silt.

Site N-3 is located near the bottom of the south-facing slope of Caribou Peak. The vegetation consists of a closed mixed forest community of black spruce, birch (Betula papyrifera), and aspen (Populus tremuloides) and a 24-cm organic mat of mosses. Seventy centimeters of silt and organic silt rests directly on bedrock.

Sites K-25, K-24, and K-23 are all located mid-slope on the south side of Caribou Peak. The three sites are all within 45 m elevation of each other and have similar equivalent latitudes (Table 1), but have considerably different vegetation types. All three sites have shallow silt soils over weathered bedrock. The vegetation at Site K-25 is a closed aspen forest with a thin 6-cm organic layer of forest litter. Site K-24 has a closed black spruce forest with trees to 8 m high and a 30-cm-thick mat of mosses. The vegetation at K-23 consists of a closed tall-shrub community of alder (Alnus crispa) up to 3 m high, with a 10-cm-thick organic mat.

Table 1
Caribou-Poker Creek Site Characteristics

Site	Landform	Hole Depth (m)	Elev (m)	Slope	Aspect	Equiv. Lat.	MAST (°C)
T-1A	Fs	10.8	230	3°	070°	66.24°	-1.8
N-3	Ns	4.6	250	5°	131°	61.65°	+0.7
K-25	Ns	16.2	390	12°	194°	53.42°	+1.9
K-24	Ns	12.8	410	12°	202°	53.79°	+0.4
K-23	Ns	15.9	435	10°	177°	55.71°	+2.2
K-2	Ns	4.6	770	2°	346°	67.13°	-1.0
K-20A	Ns	5.3	710	11°	004°	75.85°	-1.3

Fs - Retransported Silt (Frozen)
Ns - Schist

Site K-2 is located near the summit of Caribou Peak, which separates the drainages of Poker and Caribou creeks. It is an area of open dwarf-tree scrub consisting of scattered black spruce less than 3 m high with a 15-cm-thick organic mat over very thin rocky soil that overlies weathered bedrock. This site is a transition between non-permafrost areas on the south side of Caribou Peak and permafrost-underlain areas on the north side.

Site K-20A is located on the north side of Caribou Peak, 0.4 km north and 60 m below the summit. The vegetation consists of open black spruce forest with scattered alder and an 18-cm-thick mat of feather mosses and Sphagnum.

Equivalent latitude was calculated for each site as an index of potential insolation. The concept of equivalent latitude was applied by Dingman and Koutz (1974) to explain permafrost-topographic relationships. Any slope is parallel to a horizontal plane on the earth's surface at some latitude and receives the same potential insolation as that plane. The latitude of the horizontal plane is the equivalent latitude, θ', and depends on the inclination and azimuth of the slope:

$$\theta' = \sin^{-1}(\sin K \cos H \cos\theta + \cos K \sin\theta) \qquad (1)$$

where θ is the actual latitude of the slope, K is the inclination, and H is the azimuth. The equivalent latitude for each site is listed in Table 1.

GROUND TEMPERATURE RELATIONSHIPS

Figure 2 shows the mean ground temperature at each level for all sites within the watershed, representing averages of all the temperature readings taken between 1 June 1986 and 31 May 1987. This figure clearly shows that site T-1A was continuously frozen and was the coldest site recorded in the watershed. Ground temperatures at K-2 and K-20A were also found to be low in comparison to other sites in the watershed. The warmest sites were those located midslope on the south side of Caribou Peak. Overall, the highest surface temperatures were recorded at sites K-25 and K-23. The nearby site of K-24 showed a considerably lower average ground temperature pattern than the other two, probably because of vegetation differences at that site.

The Mean Annual Surface Temperature (MAST) for each site is listed in Table 1. We consider the surface to be the organic/mineral soil interface. Under a steady state condition, the mean annual temperature at any depth would be a linear extrapolation of the geothermal gradient. The MAST is determined by the projection of the mean ground temperature line to the surface (Lunardini, 1981). Since the mean ground temperature is markedly higher near the surface at several of the sites (Fig.1), we conclude the steady state condition no longer exists and we used the actual rather than the extrapolated

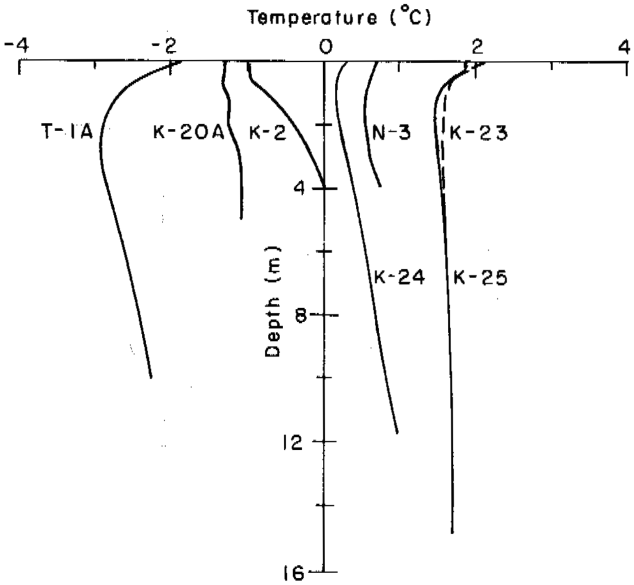

Fig. 2. Average ground and surface temperatures for all sites.

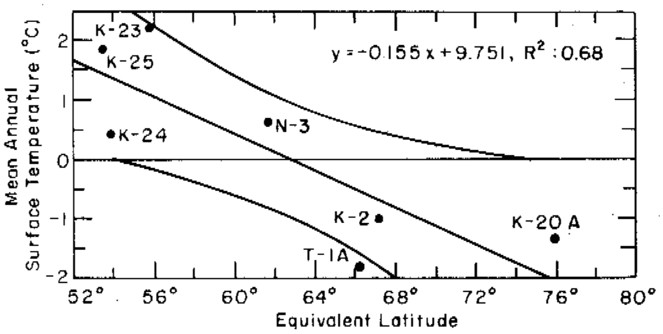

Fig. 3. Regression and correlation of mean annual surface temperature (MAST) with equivalent latitude. The curved lines show the 95% confidence interval for true mean of Y.

surface temperature for our comparison to equivalent latitude (Fig. 3). The coefficient of determination (r^2) for this relationship is 0.68. Most of the MAST differences among the sites with a similar equivalent latitude, such as K-25, K-24, and K-23, appear to be due to vegetation. The black spruce and thick moss cover of K-24 provides considerably more insulation and shading compared to the two nearby sites. The permafrost/non-permafrost boundary is represented by the intersection of the regression line with 0°C MAST (Fig. 3), which occurs at approximately 63° equivalent latitude.

The MAST at the valley bottom site, T-1A, is much lower than at any other site in the watershed. Winter inversions of the air temperature profile result in sharply lower air temperatures at the valley bottom. This site also has by far the thickest surface organic ground mat (45 cm). The moss (primarily Sphagnum spp.) tends to have a lower thermal conductivity during the summer (it is driest in June-July), which would lessen the heat flux into the ground as compared to the other sites. Site differences in depth of winter snow cover is a third major factor, but we do not have sufficient data to evaluate its effect.

The only air temperatures available for comparison are long-term annual means of -2.9°C for Caribou Peak and -4.5°C for Caribou Creek valley (Haugen et al., 1982). Applying an empirical equation developed for air and ground surface (organic/mineral soil interface) mean annual temperatures from a Fairbanks to Prudhoe Bay transect that includes the present study area, Haugen et al.(1983) found a regression relationship of

$$Y = 1.25 + 0.71X \qquad (2)$$

where X is the mean annual air temperature and Y is the MAST. The equation yields an estimated MAST of -0.8°C for the K-2 ridgetop site, and -2.2°C for the T-1A valley bottom site, close to the observed MASTs of -1.0 and -1.8°C for the two sites (Table 1).

CONCLUSIONS

The monitoring of surface and subsurface ground temperatures at seven drill hole sites in a discontinuous permafrost upland taiga environment has provided documentation of surface and subsurface temperatures for proximal permafrost/non-permafrost regimes. The measurements indicate a strong relationship between permafrost distribution and several environmental parameters; slope orientation and aspect (characterized by equivalent latitude computations), elevation and related winter air temperature inversions, and vegetation associations appear to be the most important ones. The equivalent latitude analysis yields a permafrost/non-permafrost boundary at 63°, and an empirically derived mean annual air and surface temperature equation from previous work agrees closely with the present ground surface temperature observations at the highest (Caribou Peak) and lowest (Caribou Creek valley) sites. This analysis of slope equivalent latitude, elevation-air temperature relationships, and vegetation associations has provided documentation and algorithms to permit a more accurate delineation of permafrost boundary areas in an upland taiga environment.

ACKNOWLEDGEMENTS

The authors acknowledge the contributions of Jerry Brown, formerly of USA CRREL, Hanover, N.H., who was responsible for initiating this project; Bruce Brockett, who provided technical assistance on the winter drilling work; and Anthony Zenk, who did much of the field data collection.

REFERENCES

Bilello, M A (1974).
Air masses, fronts and winter precipitation in central Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, Research Report 319.

Brown, R J E (1978).
Influence of climate and terrain on ground temperature in the continuous permafrost zone of northern Manitoba. Proc. Third Int. Conf. on Perm., 15-21.

Brown, R J E & Péwé, P L (1973).
Distribution of permafrost in North America and its relation to the environment; a review. Proc. Second Int. Conf on Perm., 71-100.

Collins, C M & Zenk, A , in preparation.
Ground temperature studies in the Caribou-Poker Creeks Research Watershed, Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, Special Report.

Dingman, S L & Koutz, F R (1974). Relations among vegetation, permafrost, and potential insolation in Central Alaska.
Arctic and Alpine Research, (6), 1, 37-42.

Forbes, R B & Weber, F R (1982).
Bedrock geologic map of the Fairbanks mining district, Alaska. Alaska Division of Geological and Geophysical Surveys, Open-file Report 170.

Foster, H L, Weber, F R, Forbes, R B & Graff, E E (1973).
Regional geology of Yukon-Tanana Upland, Alaska. Arctic Geology, American Association of Petroleum Geologists Memoir 19, 388-395.

Haugen, R K, & Brown, J (1978).
Climatic and dendroclimatic indices in the discontinuous permafrost zone of the central Alaskan uplands. Proc. Third Int. Conf. on Perm., 392-398.

Haugen, R K, Slaughter, C W, Howe, K E & Dingman, S L (1982).

Hydrology and climatology of the Caribou-Poker Creeks Research Watershed, Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report 82-26.

Haugen, R K, Outcalt, S I & Harle, J C (1983). Relationships between estimated and mean annual air and permafrost temperatures in north-central Alaska. Proc. Fourth Int. Conf. on Perm., 462-467.

Jorgenson, M T, Slaughter, C W & Viereck, L A (in press). Reconnaissance survey of vegetation and terrain relationships in the Poker-Caribou Creeks Watershed, Central Alaska. Institute of Northern Forestry, U.S. Forest Service.

Jorgenson, M T (1984). Potential insolation as a topoclimatic characteristic of drainage basins. Int. Assoc. Sci. Hydrol. Bull., (9), 1, 27-41.

Lunardini, V J (1981). Heat Transfer in Cold Climates. Van Nostrand Reinhold Company, New York.

Morrissey, L A, Strong, L L, & Card, D H (1986). Mapping permafrost in the boreal forest with Thematic Mapper satellite data. Photogrametric Engineering and Remote Sensing (52), 1513-1520.

Nelson, F & Outcalt, S I (1983). A frost index number for spatial prediction of ground-frost zones. Proc. Fourth Int. Conf. on Perm., 907-911.

Osterkamp, T E (1974). Temperature measurements in permafrost. Alaska Department of Transportation and Public Facilities, Report No. TFHWA-AK-RD-85-11.

Péwé, T L (1982). Geologic hazards of the Fairbanks area, Alaska. Alaska Geological and Geophysical Surveys, Special Report 15.

Rieger, S, Furbush, C E, Schoephorster, D B, Summerfield, H & Gieger, L C (1972). Soils of the Caribou-Poker Creeks Research Watershed, Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, Technical Report 236.

Wahrhaftig, C (1965). Physiographic divisions of Alaska. U.S. Geological Survey, Professional Paper 482.

Wu, T H (1984) Soil movements on permafrost slopes near Fairbanks,Alaska. Canadian Geotechnical Journal, (21), 699-709.