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ACTIVE LAYER THERMAL REGIMES IN AN ALPINE PASS, CHITISTONE PASS, ALASKA

by
Anthony James Brazel

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Geography)
in The University of Michigan
1972

Doctoral Committee:

Assistant Professor Samuel I. Outcalt, Chairman
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Professor Melvin G. Marcus
Professor Donald J. Portman

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PREFACE

This study represents part of an overall research program in an alpine periglacial mountain pass--Chitistone Pass, Alaska. Previous climatological studies connected with the St. Elias Mountains have not concentrated on the relation between topography and variations in microclimate. Several investigations have been carried out, but none have specifically investigated local microclimate contrasts within one varied tundra location. Also, none have investigated a mountain pass environment.

The climatological investigation conducted at Chitistone Pass, Alaska focused on topoclimatology. Many related studies were also conducted. These included geomorphology, glaciology, and botany. The project under which this research was initiated is called the High Mountain Environment Project (HMEP), which was supported by the Arctic Institute of North America and funded by the Army Research Office, Durham, North Carolina, under contract No. DAHCO 4-67C-0047, ARO-D Project No. 6408-EN, and R&D Project No. 2 M014501B52B.

Many thanks go to all the climatology assistants and to Dr. Samuel Outcalt, Dr. Donald Portman, and Dr. Melvin Marcus, who have made the analysis presented in this study possible. I am indebted to them.

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NOTATION FOR PHYSICAL ARGUMENTS

(all units c.g.s. unless noted in text)

A	allwave radiation
a	slope aspect
a'	intercept notation in multiple regression test
b	slope coefficient in multiple regression test
C	volumetric heat capacity
cm	centimeters
d	depth to 0°C plane
Fact	F-statistic
H	sensible heat flux
h	site horizon
k_s	thermal diffusivity
LE	latent heat flux
Lo	longwave outgoing radiation
lys	langleys
m	meters
mb	millibars
QR	reflected solar radiation
Q	solar radiation
Rn	net radiation

r	partial correlation coefficient
rs	Spearman's rho rank correlation coefficient
S	active layer heat flux
s	slope angle
se	standard error of the partial correlation coefficient
t	temperature in the active layer
tact	t-statistic
T	temperature
$\overline{T}$	mean temperature
U	wind velocity
W	surface area of wetness
x	volume fraction of substance in the active layer
z_o	aerodynamic roughness length
z	reference height or depth
α	albedo
ε	emissivity
λ	thermal conductivity
σ	Stefan-Boltzmann constant (8.22×10^{-11} lys/min/$^oK^4$)
ω	angular frequency of temperature oscillation (π/12 hours)

Subscripts

α	albedo
a	slope aspect

b	slope coefficient in regression analysis
g	organic matter fraction
I	incoming radiation
k_s	thermal diffusivity
m	mineral fraction in active layer
max	maximum quantity
max(1)	time of maximum quantity at depth 1 (surface)
max(2)	time of maximum quantity at depth 2 (-10 cm)
o	surface reference
or	surface diurnal range
omax	maximum value at surface
tot	daily total
w	water fraction in active layer
-10	reference depth of -10 cm
-10r	diurnal range at -10 cm
-10max	maximum value at -10 cm
1	reference height 1 (50 cm)
2	reference height 2 (250 cm)

CHAPTER I

INTRODUCTION

Definition of Topoclimatology

The term "topoclimatology," a word coined by C. W. Thornthwaite (1953), is a subdiscipline of climatology that analyzes climatic responses to changes in the earth's surface composition and topography. This subdiscipline includes a broad scale spectrum of relations, ranging from mountain barriers influencing wind systems, to understanding evaporation in the south and north sides of a moss clump.

Geiger (1965) and Thornthwaite (1953) define topoclimatology as an intermediate scale between the micro and macro scales. This scale does not have a well-defined spatial dimension, but appears to represent climatic responses to changes over areas perhaps field size compared to micro and subcontinental scales. This definition is adopted here to specify the subdiscipline of this study.

Problem Statement

The research conducted in this study represents a specific problem in topoclimatology as defined above. The basic hypothesis to be tested is that the effects of topography have an overriding influence on a site's thermal regimes in comparison with the individual site's

radiative and thermal properties in a rugged mountain location during the high sun period.

Conceptualization of the Problem

The problem of understanding active layer thermal regimes on a topoclimatic scale may be resolved by ranking controlling influences. The surface temperature of the active layer is linked with all the energy balance components, where the energy exchange is given by:

$$Rn + LE + H + S = 0, \quad (1)$$

where, Rn = net radiation,

LE = latent heat flux with the air,

H = sensible heat flux with the air,

S = heat flux in the active layer.

The term "active layer" refers to the depth of the 0°C plane in the soil.

Myrup (1969), Outcalt (1971a), and Outcalt (1972c) have presented a model framework of the energy exchange which explicitly specifies the controlling geographic factors that regulate energy exchange components and the thermal regimes of the substrate material. These factors are:

(1) soil volumetric heat capacity (C)

(2) soil thermal diffusivity (k_s)

(3) surface roughness (z_o)

(4) albedo (α)

(5) slope angle of the surface (s)

(6) site horizon (h)

(7) slope aspect (a)

(8) depth to the 0°C plane (d)

(9) emissivity (ε)

(10) wetness of the surface. (W)

These geographic variables regulate the surface equilibrium temperature--the unique temperature which balances the energy exchange equation (Outcalt, 1971a). The geographic variables are site properties which in concert with solar radiation and local weather determine the thermal response of the active layer. The conceptual framework of this study is summarized as:

I. Solar Radiation (Q)

II. Site Properties:

a. Topographic:

slope (s)

aspect (a)

site horizon (h)

roughness length (z_o)

b. Radiative:

albedo (α)

emissivity (ε)

c. Thermal:

heat capacity (C)

diffusivity (k_s)

depth to 0°C plane (d)

III. Thermal Responses:

a. Surface:

mean diurnal temperature	($\bar{T}_o$)
diurnal temperature range	(T_{or})
maximum temperature	(T_{omax})

b. Substrate:

mean diurnal temperature	($\bar{T}_{-10}$)
diurnal temperature range	(T_{-10r})
maximum temperature.	(T_{-10max})

The substrate temperature analyzed in this study is the -10 cm depth. Under numeral I. above, changes in the meterological conditions are considered by analyzing the relationship of the geographic variables and the thermal regimes under differing solar radiation conditions. An explicit evaluation of the influence of advective effects and turbulent transfer is not included in this study because of instrumental limitations. However, it has been found that there are no strong contrasts of the 2 meter air temperature, wind, and relative humidity among the sites (Brazel, 1970).

This thesis will examine the sensitivity of the active layer thermal regimes to variations in the surface conditions as determined by topography and thermal/radiative properties. The strategy of the study is to consider solar radiation as a forcing function conditioned by site properties resulting in a unique response of active layer temperatures.

CHAPTER II

STUDY LOCATION AND SAMPLING METHODS

Study Location

Description of the Study Area

The research was carried out in Chitistone Pass, Alaska (61°36'14"N and 142°03'35"W), shown in Figures 1 and 2. The pass is located in the Wrangell Mountains of Southeast Alaska, and is 1773 m above sea level. It forms a local hydrological divide considerably above the tree line at this latitude, and is a typical alpine tundra environment. Only for a short summer season is the pass snow-free and typified by exposed ground and alpine tundra vegetation.

The subsurface layer in the pass is permanently frozen except for a shallow active layer about 1 m deep. In early May, 90% of the pass is snow covered to a depth of about 2 m (Fig. 3). Only slope and knoll exposures have little or no snow cover. Most of the snow blanket disappears by the end of July. The active layer stratigraphy is highly variable in composition over short distances, and contains many periglacial features such as patterned ground, stripes, mud boils, rings, morainal deposits, stream terraces, and talus debris. Solifluction is active. The bedrock and weathered material in the pass are of volcanic origin, consisting of vesicular basalt. Only in localized zones, where

Figure 1

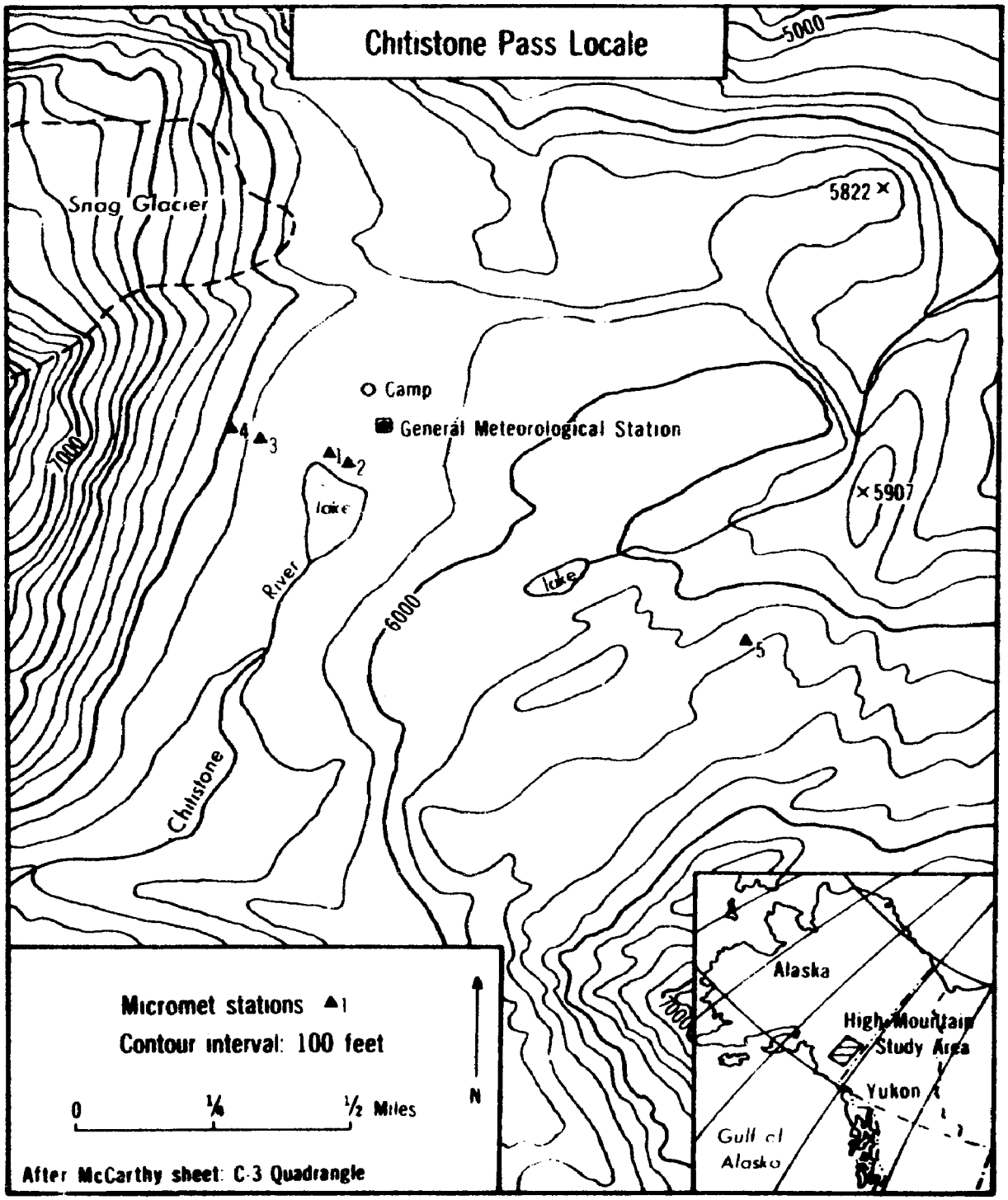

Chitistone Pass Locale
5000
Snag Glacier
5822 ×
Camp
General Meteorological Station
4
3
1
2
7000
lake
River
6000
×5907
lake
5
Chilistone
Micromet stations ▲1
Contour interval: 100 feet
0
¼
½ Miles
N
After McCarthy sheet: C-3 Quadrangle
Alaska
7000
High Mountain
Study Area
Yukon
Gulf of
Alaska

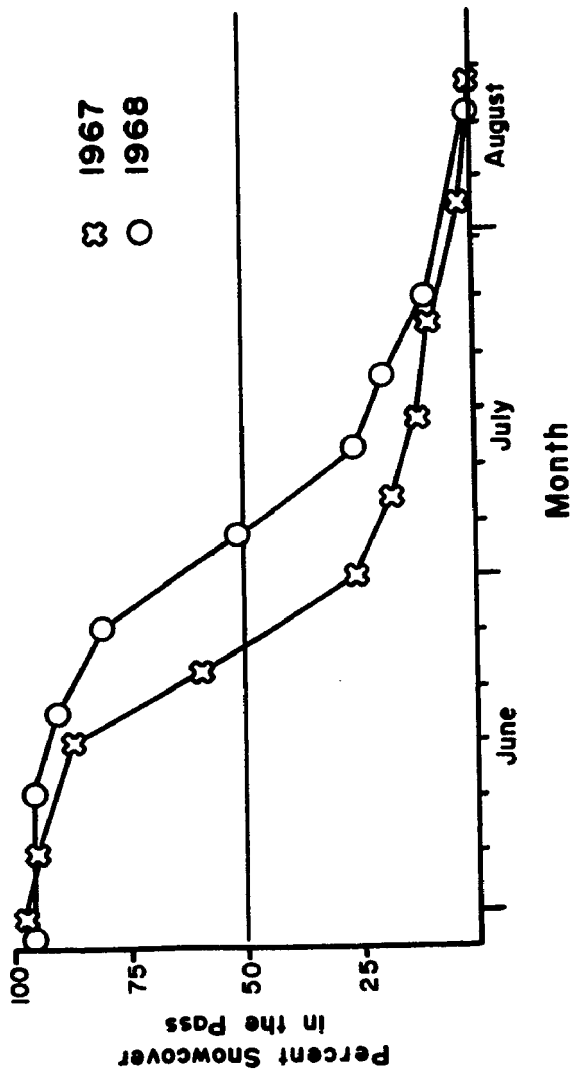


Figure 2. Aerial photo of Chitistone Pass area (U.S.G.S.; 15 August, 1957). Scale: 1/39,000.

▲ = Research station
● = Skolai landing strip
••• = Environmental transect

Figure 3

Snowcover in the Pass



vegetation is continuous, is an organic layer found in the regolith and soil. Local relief in the pass (5 m to 15 m) is expressed as ridges and knobs resulting from differential weathering and erosion. Surficial deposits mantle the bedrock to a thickness of 40 to 100 cm in most places; the depth of unconsolidated debris rarely exceeds 125 cm.

The pass orientation (Fig. 1) is SSW to NNE with predominantly NW and SE facing slopes on either side of the pass.

Climate

Chitistone Pass lies transitional between coastal and continental influences. For the period of record, the pass climate is primarily the product of marine air movement from the Gulf of Alaska--conditions promoting very moist and cloudy weather for long periods during the alpine summer. Table 1 gives a summary of weather data recorded at Chitistone Pass for the period 1967-69. In reworking the data, it is found that during 50% of the summer the region was dominated by conditions of SW winds, much cloud cover, and high humidity (see Table 2). Very few periods of clear, calm weather were encountered.

The mean summer period temperature is 4.7°C. Analysis of air temperature differences with elevation indicated that no marked inversions occurred within the pass confines (Brazel, 1970). During the observation period considered in this study no major freeze-thaw cycles were experienced. On only one day was the air temperature below the freezing point. Thus, freeze-thaw effects within the active layer can be neglected.

The wind direction pattern is virtually the same as the pass orientation, with SW winds channeling through the pass most of the time,

TABLE 1

CLIMATIC SUMMARY, CHITISTONE PASS, ALASKA, 1967-1969[a]

Climatic Factor	June 9- Aug. 18, 1967	May 31- Aug. 16, 1968	May 25- Aug. 14, 1969
Mean daily temperature (°C)	5.2	4.7	4.4
Mean maximum daily temperature (°C)	6.0	9.2	7.9
Mean minimum daily temperature (°C)	1.8	1.5	1.1
Extreme maximum daily temperature (°C)	15.0	16.6	20.6
Extreme minimum daily temperature (°C)	- 1.5	- 6.2	-10.0
Precipitation (cm. of snow)	3.3	53.7	24.1
Precipitation (cm. of rain)	13.3	11.0	28.3
Mean daily radiation (lys)	409.0	463.5	430.4
Extreme maximum daily radiation (lys)	681.6	691.1	657.6
Extreme minimum daily radiation (lys)	93.1	164.4	148.8
Mean insolation index	0.456	0.507	0.447
Mean cloudiness (tenths)	7.5	6.9	7.2
Mean wind velocity (m/sec)	3.1	2.5	3.4
Maximum wind velocity (m/sec)	15.8	9.5	11.3
Mean relative humidity (%)	84.9	76.5	79.3
Maximum relative humidity (%)	100.0	100.0	100.0
Minimum relative humidity (%)	33.0	36.0	33.0
Mean pressure (mb)[b]	--	819.1	834.8
Extreme maximum pressure (mb)[b]	--	828.9	847.5
Extreme minimum pressure (mb)[b]	--	800.2	817.6

[a]Table is extracted from Marcus (1971, 19).

[b]Barometric pressure data are correct relative to each other for each year. Absolute pressure values are subject to a constant calibration error for each year. Absolute values for the three years should not be compared.

TABLE 2

PERCENTAGES OF SUMMER WEATHER CONDITIONS CHITISTONE PASS (1967-69)[a]

% of time for given condition[b]	Weather condition
50%	SW winds (light to moderate), 8/10-10/10ths cloud cover, 70-100% relative humidity
24%	NE winds (light to moderate), 0/10-4/10ths cloud cover, 50-70% relative humidity
20%	Variable wind direction, variable cloud cover, no marked relative humidity pattern
6%	Clear skies, low wind speed, no predominant wind direction, low relative humidity (40-60%)

[a]These conditions are based on the grouping of daily average weather elements from general weather station data obtained from Marcus (1968), Kolberg and Brazel (1969), and Benjey (1970). The data suggested four groups of general weather conditions based on mean daily values. No detailed analysis in terms of corresponding air mass associations is presented in this study.

[b]Number of daily observations out of the total number of observations times 100% that displayed the particular weather conditions.

or brief periods of NE winds from the opposite direction. No slope wind systems of significant magnitude were detected in the pass during the observation periods.

Major weather elements such as wind, air temperature, precipitation, and cloud cover are relatively homogeneous elements for the pass as a whole. Observations of these variables indicated that there was very little spatial variation of theseeelements within the pass (Brazel, 1970).

Sampling Methods

Sites

In order to test the specified hypothesis, a sample network of sites was chosen in the pass (see Fig. 1). The exact locations were dictated by project constraints, but an attempt was made to sample varying topographic, active layer composition, and thermal radiative property differences within the pass. Figures 4 to 7 show the recording system of each site and Plates 1 to 6 the general site locales.

The active layer stratigraphies are illustrated in Figure 8. Stations 1 and 2 are typical surfaces in the flatter portions of the terrain, while stations 3, 4, and 5 typify large portions of the western and eastern parts of the pass slopes.

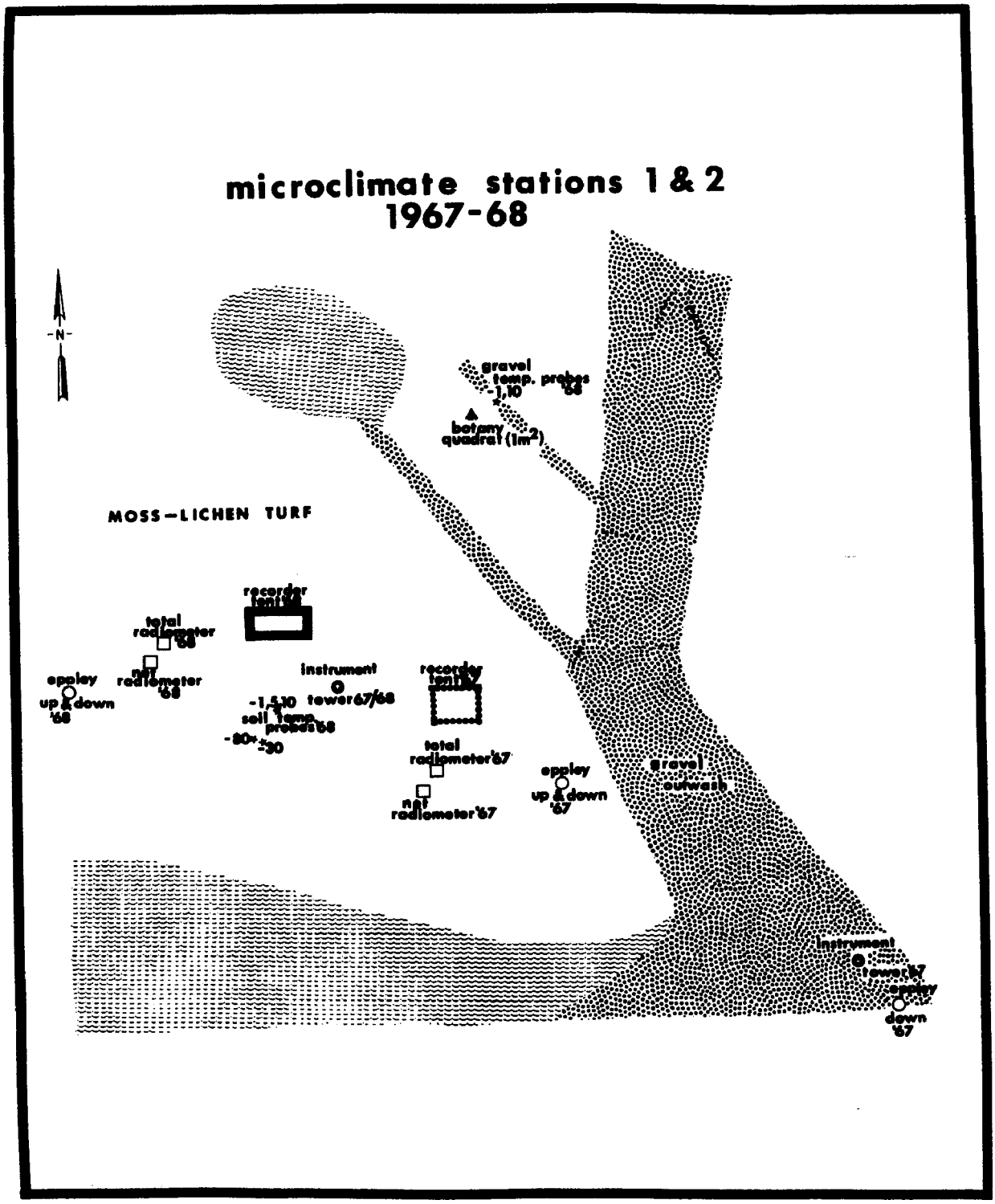
To accomplish the specific objectives outlined before, the following variables were recorded manually on an hourly basis for 21 days in 1967 and 1968 (see Table 3 for periods of observation):

(1) solar radiation (Q)

(2) albedo (α)

(3) surface temperature (T_o)

Figure 4


microclimate stations 1 & 2
1967-68
-N-
gravel
temp. probes
-1,10
'68
botany
quadrat (1m²)
MOSS—LICHEN TURF
recorder
total
radiometer
'68
net
radiometer
'68
eppley
up & down
'68
instrument
tower 67/68
-1,5,10
soil temp.
probes '68
-80+ -30
recorder
total
radiometer '67
net
radiometer '67
eppley
up & down
'67
gravel
outwash
instrument
tower '67
eppley
down
'67

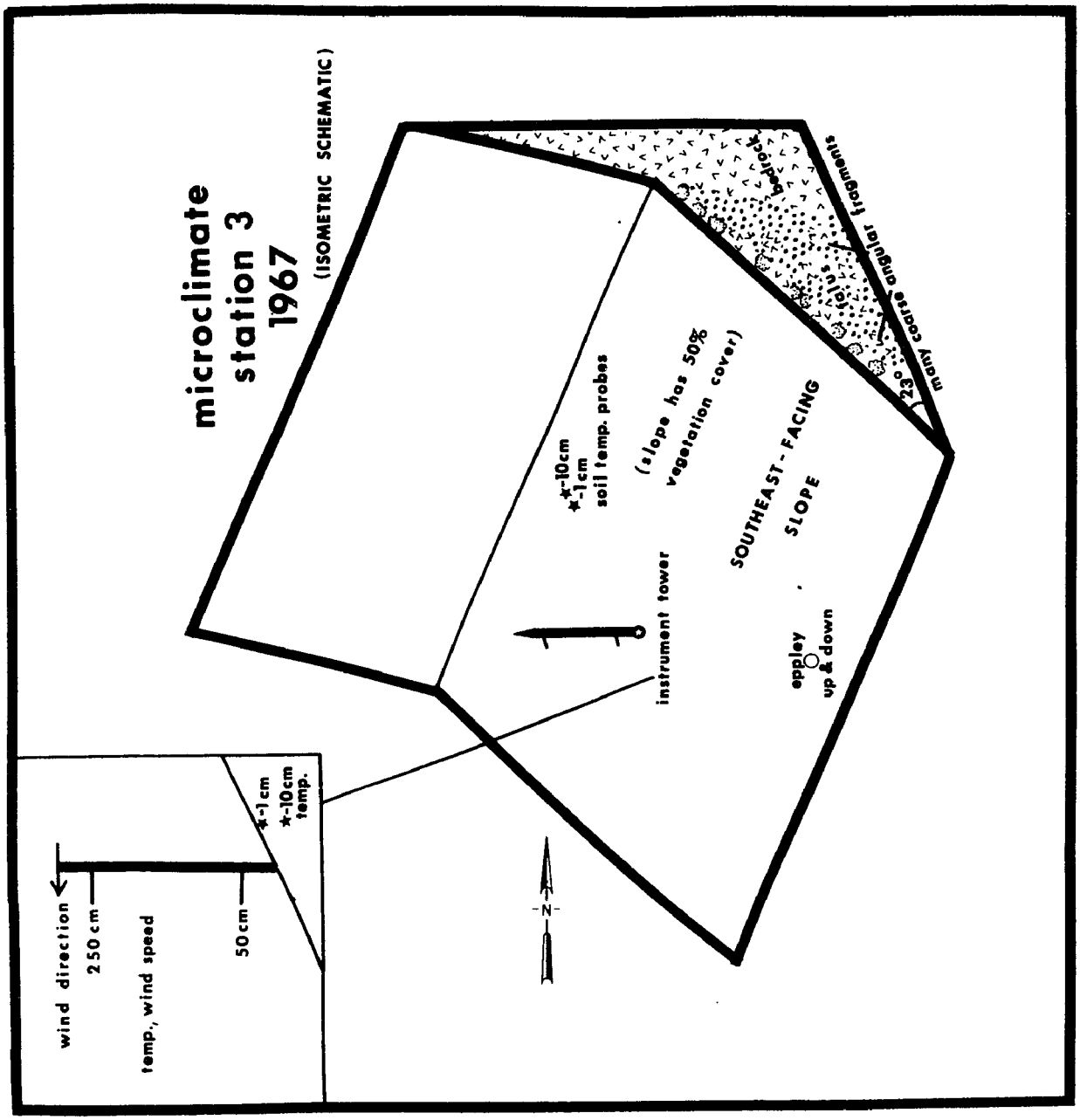

microclimate
station 3
1967
(ISOMETRIC SCHEMATIC)
many coarse angular fragments
bedrock
33°
soil temp. probes
*-10cm
*-1cm
(slope has 50%
vegetation cover)
SOUTHEAST-FACING
SLOPE
instrument tower
eppley
up & down
N
wind direction
250 cm
temp., wind speed
50cm
*-1 cm
*-10cm
temp.

Figure 5

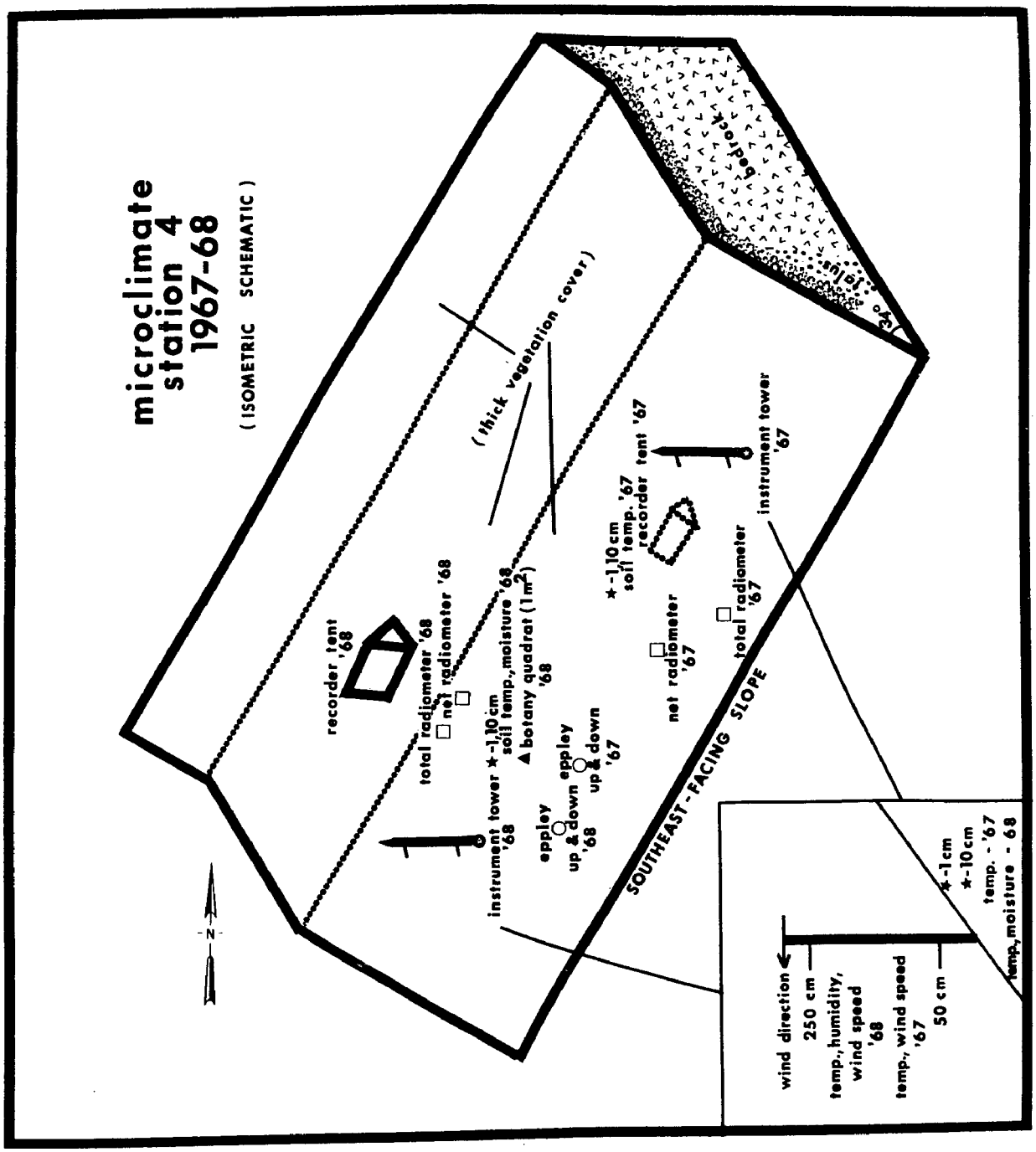

microclimate
station 4
1967-68
(ISOMETRIC SCHEMATIC)
recorder tent '68
total radiometer '68
net radiometer '68
instrument tower '68
★-1,10 cm soil temp.,moisture '68
▲ botany quadrat (1 m²)
appley
up & down '68
appley
up & down '67
★-1,10 cm soil temp. '67
recorder tent '67
net radiometer '67
total radiometer '67
instrument tower '67
(thick vegetation cover)
SOUTHEAST-FACING SLOPE
wind direction
250 cm
temp., humidity, wind speed '68
temp., wind speed '67
50 cm
★-1 cm
★-10 cm
temp. - '67
temp., moisture - 68
N

Figure 6

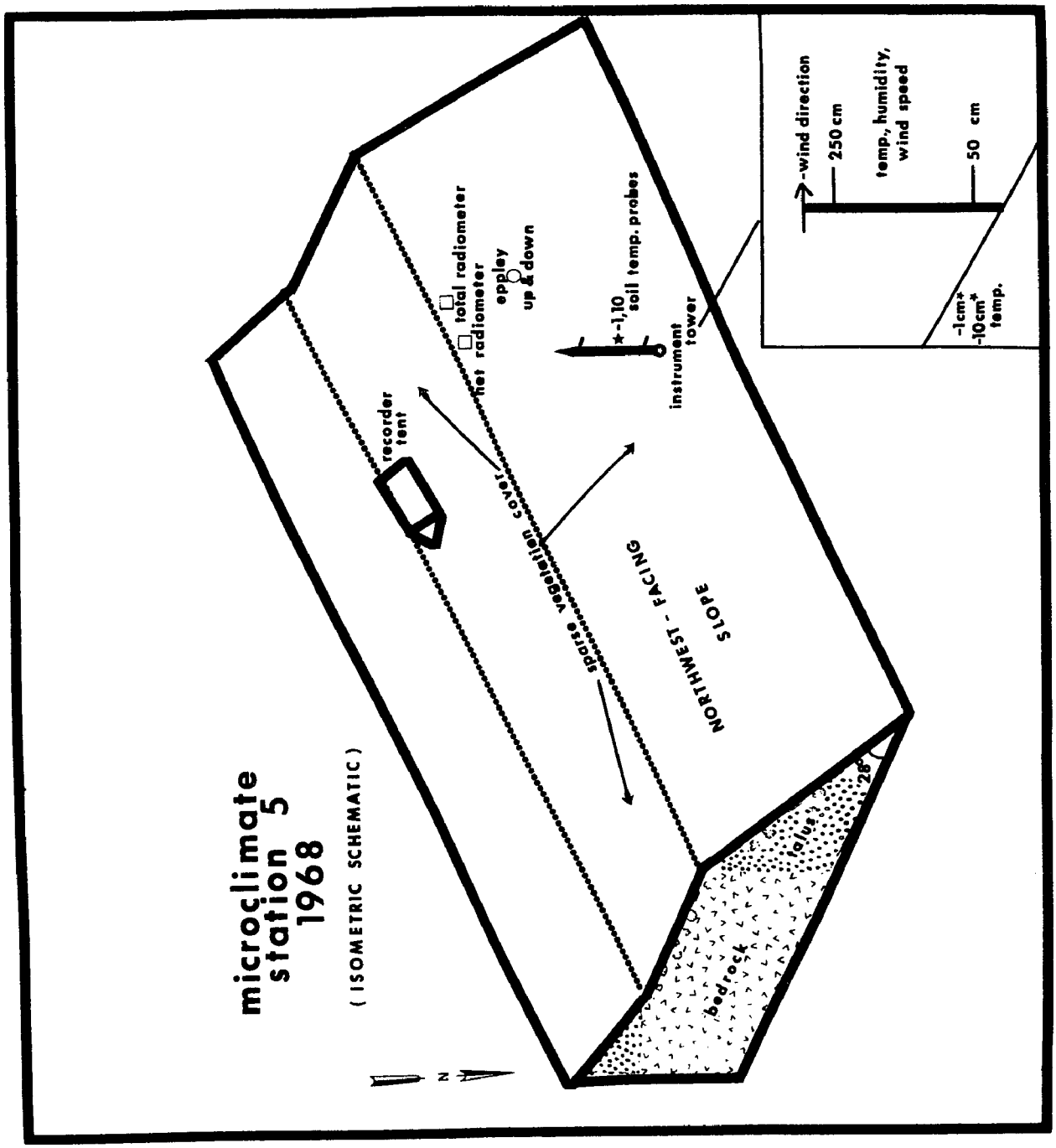

microclimate
station 5
1968
(ISOMETRIC SCHEMATIC)
N
recorder tent
total radiometer
net radiometer
epply
up & down
★-1,10
soil temp. probes
instrument tower
sparse vegetation cover
NORTHWEST - FACING
SLOPE
bedrock
28°
-wind direction
250 cm
temp., humidity,
wind speed
50 cm
-1cm*
-10cm*
temp.

Figure 7

PLATE 1



General locale of sites 1 and 2. Stream channel is site 2 and site 1 is at tower location in the photo.

PLATE 2



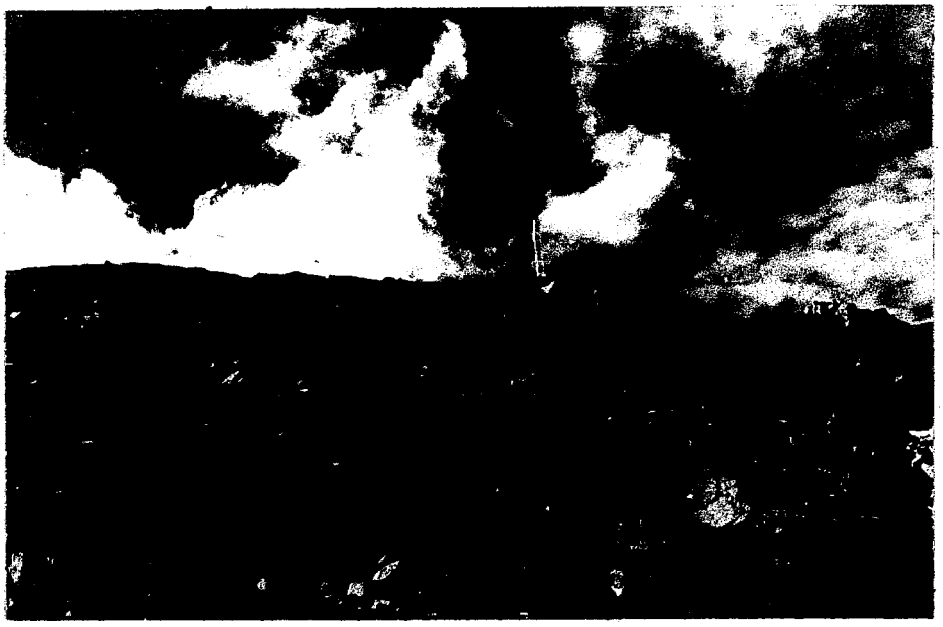
Sites 3 and 4 on SE Facing Slope. Sites are at points where towers are shown in the photo.

PLATE 3



Site 3. Specific conditions around site 3.

PLATE 4



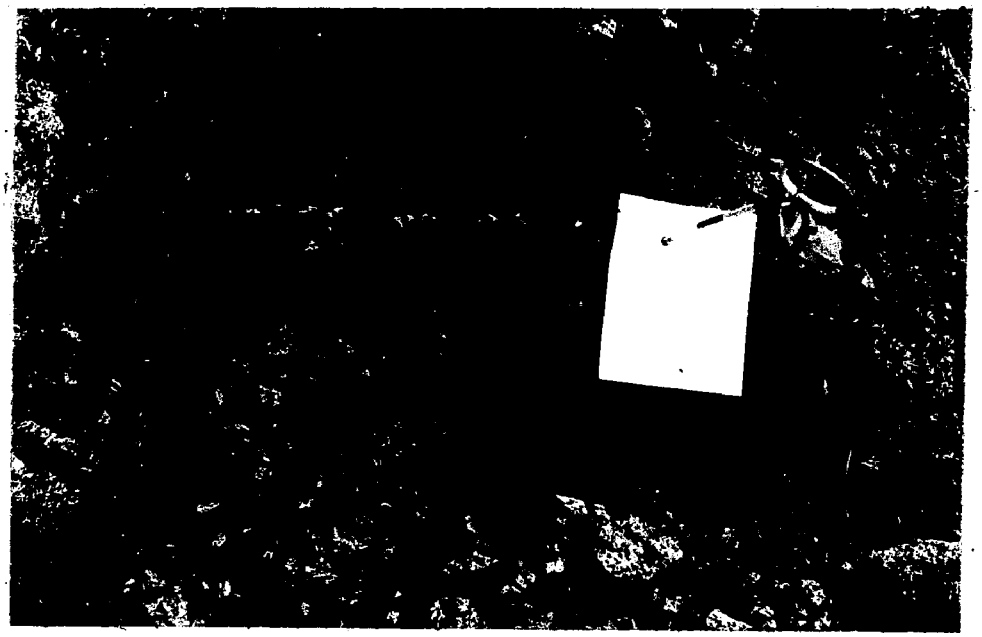
Site 4. Willow and dryas mats at site 4.

PLATE 5



General locale of site 5. Site located on a knoll in the foreground.

PLATE 6



Site 5 surface condition.· Coarse to fine basalt scree and rubble composes the surface.

Figure 8

STATION STRATIGRAPHY

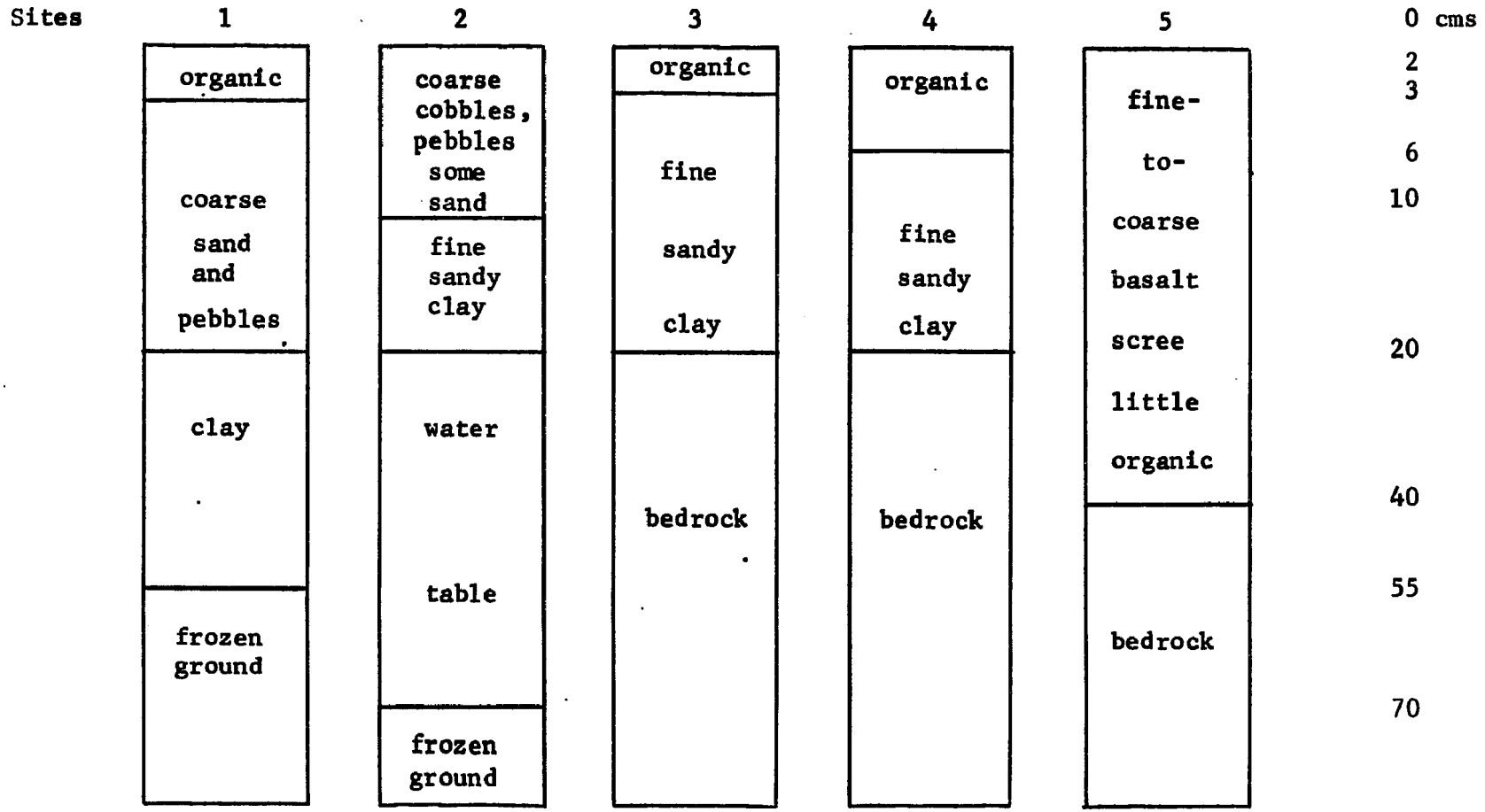


TABLE 3

TOPOCLIMATE OBSERVATION DATES AND ACCOMPANYING WEATHER CONDITIONS[a]

	Observed Stations	Max. Temp. (°C)	Mean Temp. (°C)	Min. Temp. (°C)	Ppt. (cms)	Insol. Index	Wind Speed (m/sec)	Wind Dir.	Clouds (tenths)	Relative Humidity (fraction)
1967										
13 July	1,2,3,4	12.8	8.7	4.3	TR	0.68	4.0	NE	7.4	0.79
14 July	1,2,3,4	12.5	9.2	6.1	0.66	0.54	2.0	NE	7.8	0.78
15 July	1,4	14.8	10.1	5.5	TR	0.62	1.5	NE	5.3	0.75
22 July	1,4	8.3	5.4	2.8	0.25	0.42	5.8	SW	8.6	0.93
24 July	1,4	8.8	6.3	3.4	TR	0.30	4.9	SW	9.1	0.77
30 July	1,2,3,4	9.9	6.6	4.6	--	0.46	6.3	SW	9.3	0.87
31 July	1,2,3,4	7.3	4.2	2.5	TR	0.40	6.3	SW	9.4	0.95
1 Aug.	1,2,3,4	7.8	4.4	1.9	0.71	0.40	4.6	SW	9.9	0.99
2 Aug.	1,2,3,4	8.1	5.2	3.3	0.28	0.35	1.4	--	9.6	0.93
3 Aug.	1,2,3,4	11.1	7.1	4.4	TR	0.40	1.1	N	7.0	0.82
4 Aug.	1,2,3,4	11.3	7.4	2.8	--	0.66	3.2	SW	4.5	0.81
5 Aug.	1,2,3,4	8.3	6.2	4.2	0.03	0.30	2.3	SW	10.0	0.90
6 Aug.	1,2,3,4	15.1	9.8	5.5	TR	0.48	2.2	SW	7.9	0.84
7 Aug.	1,2,3,4	13.1	8.4	4.4	0.05	0.51	2.3	SW	7.6	0.78
8 Aug.	1,2,3,4	8.3	5.5	3.6	0.46	0.36	3.9	SW	8.3	0.86
9 Aug.	1,2,3,4	8.8	4.2	1.9	--	0.56	5.7	SW	6.4	0.85
10 Aug.	1,2,3,4	6.7	3.2	0.4	0.13	0.53	4.7	SW	6.9	0.91
11 Aug.	1,2,3,4	6.1	3.1	-0.1	0.08	0.44	7.7	SW	8.0	0.87
1968										
9 July	4,5	7.8	3.9	1.9	0.10	0.31	2.4	--	9.5	0.85
10 July	4,5	9.2	5.0	2.3	0.25	0.39	1.7	--	8.0	0.89
14 July	1,4	9.2	3.9	0.7	--	0.68	1.4	--	4.0	0.74
15 July	1,4	11.4	6.5	0.8	--	0.59	0.9	--	3.2	0.60
20 July	1,5	13.6	8.9	4.6	0.03	0.57	1.3	--	5.7	0.64
21 July	1,5	15.3	9.7	5.0	TR	0.58	1.4	--	4.2	0.65
1 Aug.	1,4,5	7.8	4.6	2.8	0.13	0.63	2.0	SW	8.0	0.88
5 Aug.	1,4,5	10.7	7.1	3.3	TR	0.54	4.1	NE	5.7	0.70

[a]All values are daily totals or means.

(4) -10 cm temperature (T_{-10})

(5) emissivity (from T_o and Lo) (ε)

(6) wind speed at two levels. (U)

Other variables measured on a less frequent basis were:

(1) soil moisture (x_w)

(2) depth to 0°C plane. (d)

Table 3 lists stations simultaneously manned and the dates of observations. General weather conditions are listed in the table to indicate the nature of the sampling period weather.

Instruments

Solar Radiation

For quantifying the solar radiation input to the active layer surface, a 10-junction Eppley Pyranometer "180°" Pyrheliometer was utilized and mounted at 1 m height above each of the respective surfaces, and in such a position that the flat plate ring element was parallel to the surface. It is assumed that the flat plate was recording equal amounts of solar radiation to that being received on the active layer surface. Solar wavelengths of 0.28 to 5.0 microns are transmitted by the glass bulb of the pyranometer with uniform transmission over the range of 0.35 to 2.5 microns.

The surface albedo was measured by inverting the pyranometer and obtaining the reflected solar radiation. The reflected divided by the incoming radiation constitutes the albedo.

Active Layer Temperature

In this study, use is made of a Model 301 small brass capsule (5/16" long and 0.072" diameter) containing an insulated No. 36 gage B & S copper-constantan couple, manufactured by C. W. Thornthwaite Associates. The capsule was positioned just below the surface at each station to obtain an estimate of the surface temperature. It was placed so that it was barely visible from 1 m above the ground. This procedure is similar to that of Ahrnsbrak's (1968). This was done to minimize as much as possible strong solar heating of the capsule. Ideally, a non-surface contact instrument would give a better approximation of the active layer surface temperature (Outcalt, 1971b). With a 0.0625' diameter insertion rod, a similar unit was placed at -10 cm in the active layer.

Longwave Outgoing Radiation

In order to estimate the emissivity of the surface, longwave outgoing radiation was measured by the use of Beckman-Whitley Net Allwave and Total Incoming Aspirated Radiometers. The combination of net radiation, reflected shortwave radiation, and total allwave incoming radiation allows for the evaluation of longwave outgoing radiation by:

$$A_I - Rn - QR = Lo, \tag{2}$$

where A_I = allwave incoming radiation,

Rn = net radiation,

QR = reflected shortwave (solar) radiation.

Since also,

$$Lo = \epsilon \sigma T_o^4, \tag{3}$$

where T_o = surface temperature,

ε = emissivity,

and σ = the Stefan-Boltzmann constant,

emissivity can be estimated for each recording site by setting equation (2) equal to (3) and solving for emissivity.

Wind Speed

Aerodynamic roughness was estimated during adiabatic conditions by the use of Belfort 5-349 series totalizing anemometers positioned at 50 and 250 cm above each active layer surface. Adiabatic conditions were identified by analyzing air temperature gradients between 50 and 250 cm. Air temperature sensors consisted of radiation-shielded thermocouples manufactured by C. W. Thornthwaite Associates.

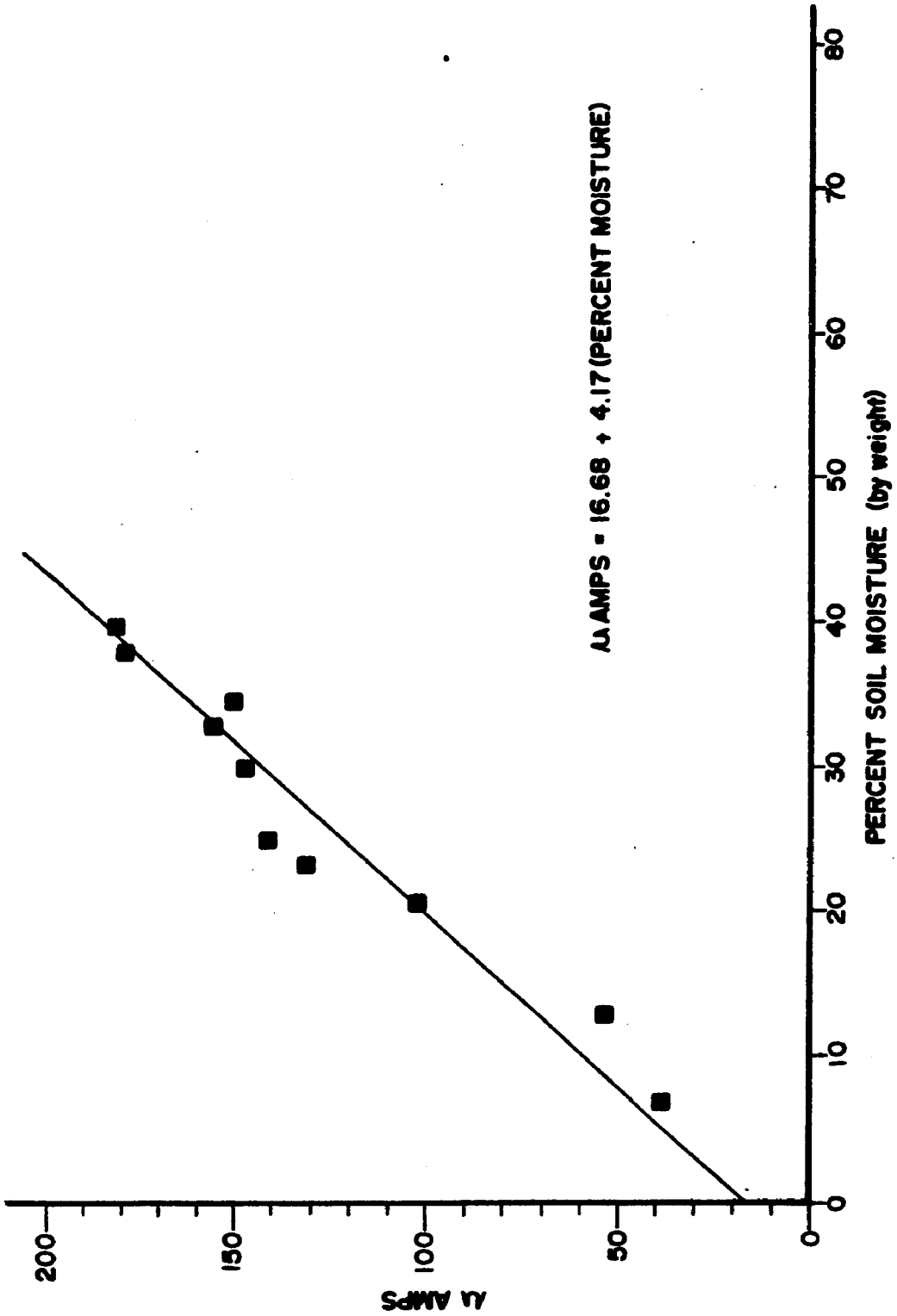
The accuracy of the wind sensors is very limited and restricts the accurate determination of turbulent transfer and advective influences on active layer thermal regimes.

Soil Moisture

Volumetric soil moisture was measured at -0.5 and -10 cm below the surface with a Model MC-300 A Soil Test Soil Moisture Meter. The apparatus consists of moisture cells of Fiberglas plates 1" by 1/2" and 1/8" thick, and waterproof thermistor units connected to a 90 cycle AC ohmmeter. Figure 9 depicts a sample calibration curve produced by oven-drying and weighing of active layer samples at the same time microampere measurements of soil moisture were made. For each site a calibration curve was drawn. Only for the 1968 season was moisture observed, and hence hourly measurements are unavailable for most observation periods.

Figure 9

Calibration Correlation Between Microamperes and Percent Soil Moisture, Station 1, 1968 (-0.5 cm level)



Depth to 0°C Plane

Average weekly frozen ground depths were monitored at Chitistone Pass for the 1968 season, and fewer such measurements for the 1967 season. However, average seasonal depths can be approximated, and also average observational depths in this study.

Recording System for Temperature and Radiation

Temperature and radiation were recorded manually. A 8690 Single Range Millivolt Leeds & Northrup Potentiometer was used (with a reference ice bath for temperatures) as an indicating device, and values for radiation and temperature were computed by the use of instrument calibration coefficients. Hourly interval data derived by averaging 20 minute instantaneous observations are used in this study.

Data Characteristics

A review of Table 4 shows that relative success has been achieved in data collection to analyze the problem statement. The table specifies in the left hand column the data requirements to comprehensively study the problem. The right hand column indicates the character of available data. In most cases the nature of available data is sufficient to analyze the problem statement, but there are major restrictions in analyzing diurnal relationships of moisture and active layer depth. Also, due to instrument limitations, variations of aerodynamic roughness and emissivity from site to site can not be explicitly presented.

TABLE 4

DATA CHARACTERISTICS OF THE STUDY

Necessary data for the comprehensive testing of the hypothesis	Character of available data
Clear and cloudy weather	Most of the data includes cloudy weather conditions. Only a few clear periods were investigated.
Known or evaluated soil thermal properties	Heat capacity partitioning achieved; diffusivity approximations obtained by analyzing surface and -10 cm temperatures.
Reliable surface and -10 cm temperatures	Use is made of contact thermocouples. Not ideal for surface temperature measurements.
Solar radiation and albedo	Accurate fast response pyranometers were used and data are available.
Slope, aspect, and site horizon	Sites representative of major slope orientations in the pass. Brunton compass used to map sky obstruction.
Active layer depth	Measured as a mean for the season. Diurnal period investigations lacking.
Soil moisture	Mean seasonal data available. Diurnal variations at sites 1 and 4 available.
Emissivity	Because of the indirect method of estimation, differences from site to site can not be accurately determined.
Roughness length	Impossible to estimate for the sites as the probable instrument error is the same order of magnitude as the recorded differences.

CHAPTER III

DETERMINATION OF TRANSFER VARIABLES

Methods of Determination

Topographic Properties

Site Horizon (h), Slope (s), and Aspect (a)

Table 5 and Figure 10 show the magnitude of the site horizon effect for solar radiation reception. If large portions of the sky are obstructed by mountains, solar radiation reception will be affected, particularly the direct beam solar radiation component.

Site horizon charts (similar to those shown by Geiger, 1965) are shown in Figure 10 and were constructed by field mapping of the local horizon of each site with a Brunton Compass. These figures illustrate the relation between the solar path and local horizon obstruction to the solar path.

The periphery of the circles represent no site horizon obstruction. For a given azimuth, as obstruction by a mountain slope to the local sky horizon increases, the degree of obstruction will range from 0° on the periphery of the circle to 90° at the center of the circle. The irregular outline of connected x points prescribes the degree of local sky obstruction for any azimuth around the local site. Solar path curves in relation to these irregular-like obstruction curves

TABLE 5

SOLAR ELEVATION, AZIMUTH, AND DECLINATION[a]

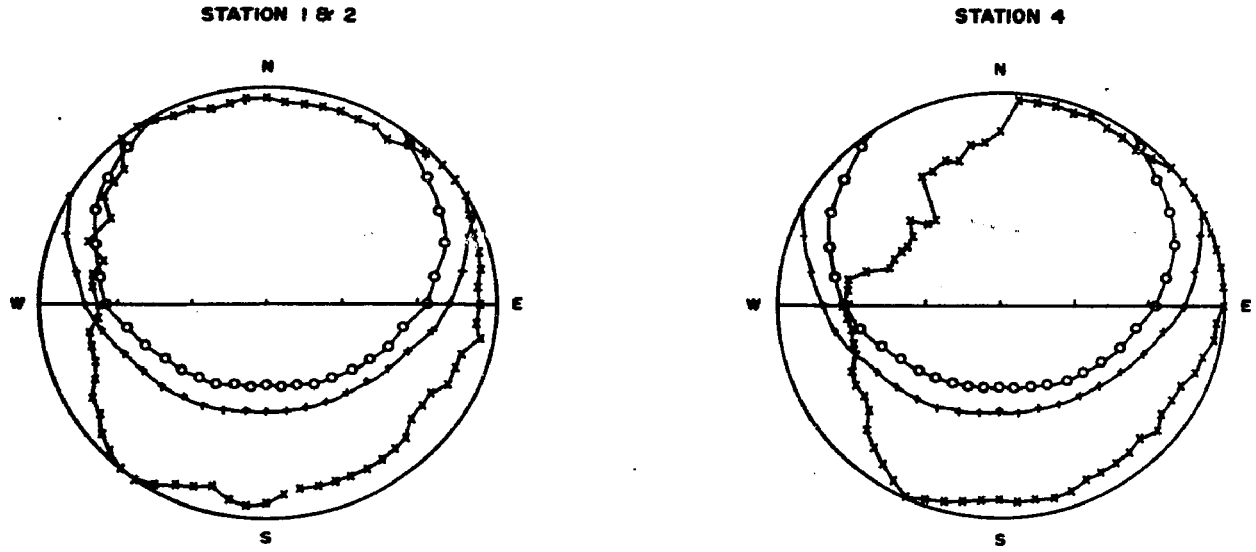
Azimuth	(Dec. = 23.5) Solar Elevation[b]	(Dec. = 15.0) Solar Elevation[b]
40	2	0
50	7	0
60	11	0
70	15	5
80	22	12
90	26	17
100	33	23
110	38	29
120	43	33
130	46	37
140	49	40
150	51	42
160	53	44
170	53	45
180	54	45

[a]From List (1949).

[b]Azimuths 180° through 320° proceed in reverse order and are equal to 180° to 40°. Also for azimuths 0° to 40° and 320° to 360°, solar elevation is equal to zero for June 23 and August 13.

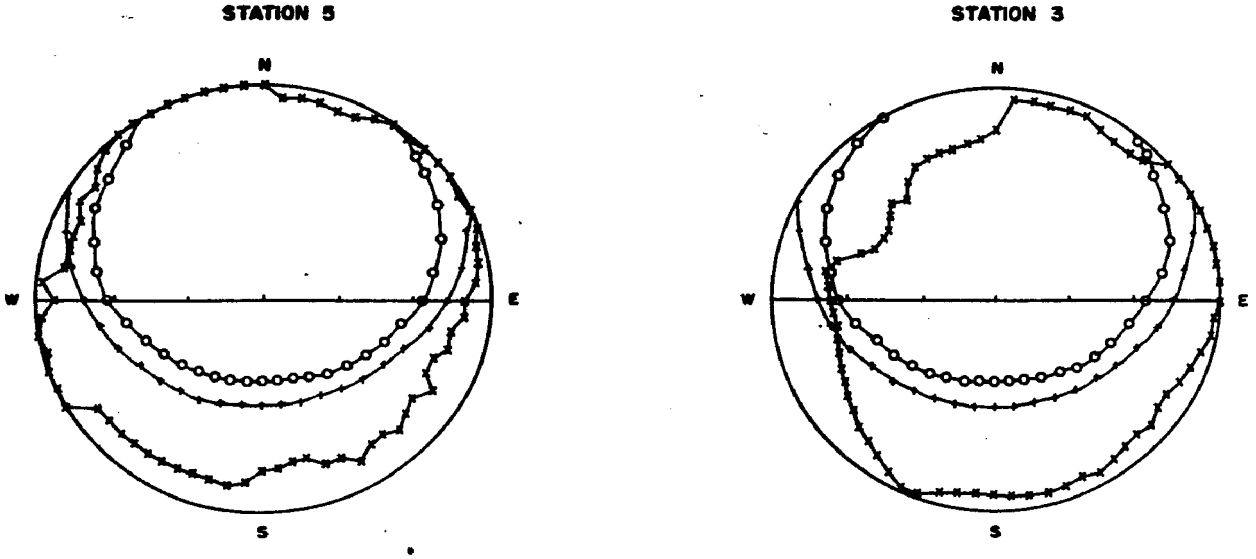
Figure 10

Site Horizons and Sun Paths



23 JUNE and 12 AUGUST
brackets field season

All horizons were field observed
with Brunton compass at each station.



reveal periods of the day when direct beam radiation becomes nil.

To give an example of the effect for the 5 sites at Chitistone Pass, solar paths for June 23 and August 13 are shown on the figures. These two dates are before and after the period of observation used in this study. Azimuths and elevations of the sun for these dates were extracted from List (1949) and are given in Table 5.

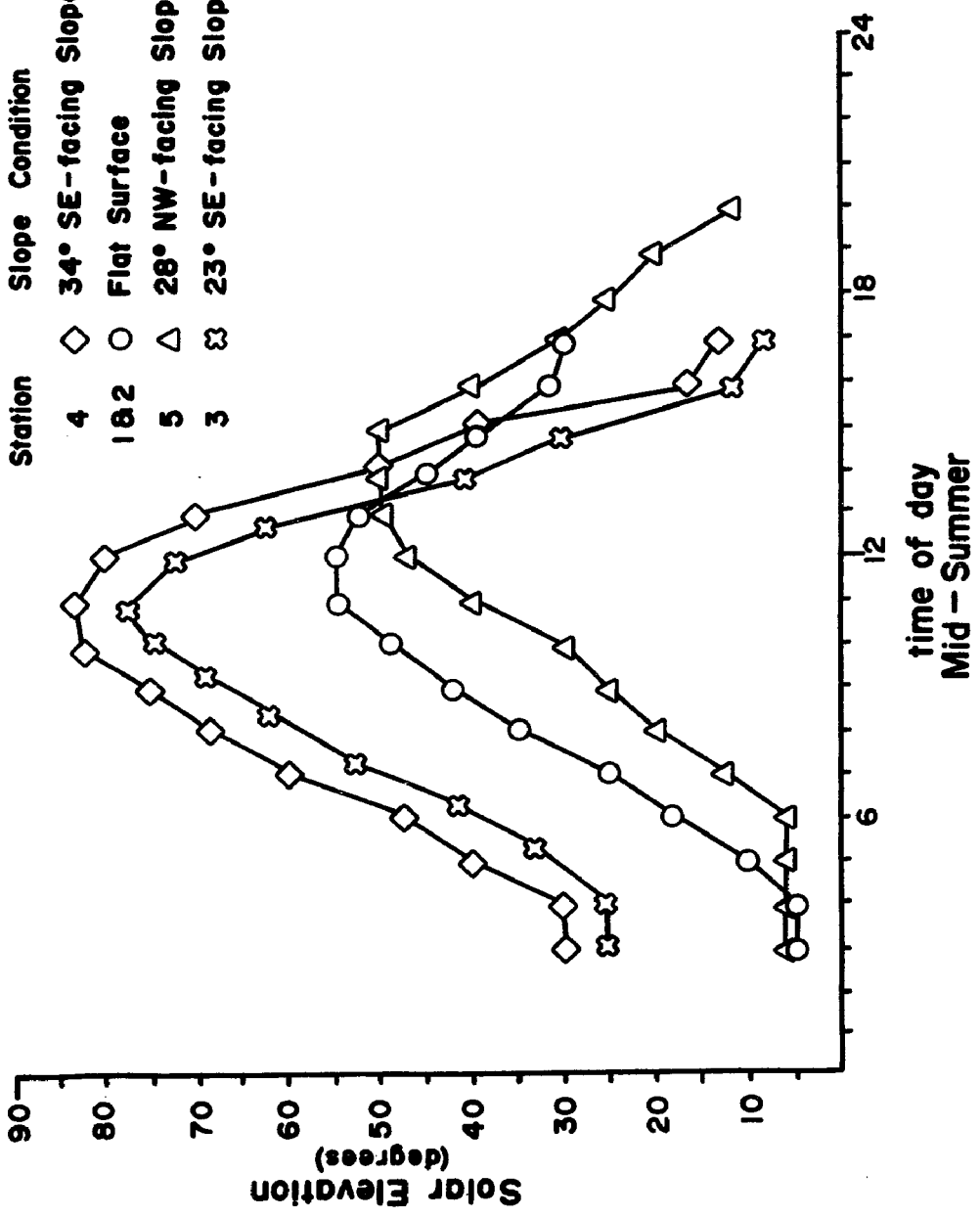
The figures indicate that very little obstruction occurs at each site, although this factor may be important elsewhere in nearby local areas of more rugged relief. Late afternoon is the only time of some horizon obstruction, so that most of the day this factor for these sites is unimportant.

The influence of slope and aspect is considerable. The station sites chosen represent slopes that occur most frequently in the pass--34° SE facing aspects, 23° SE facing aspects, 28° NW facing aspects, and level terrain. The value of slope angle was determined by Brunton Compass mapping techniques.

Figure 11 illustrates the diurnal solar elevation during the observation period (15 July) in reference to slope angle(s). The predominant features are the large differences in both amplitude and number of hours of exposure (due to both slope and aspect). For exposure time, the ranking is 14 hours for sites 3, 4, and 5, and 17 hours for sites 1 and 2. Solar elevations range from 50° (site 5), 55° (sites 1 and 2), 78° (site 3), to 83° (site 4).

Figure 11

Site Solar Elevations



Surface Radiative Properties

Albedo

Albedo measurements, which were described in a previous section, were taken relative to the slope of the surface for those sites on sloping terrain. This was achieved by tilting the Eppley plate sensor downward toward the surface and parallel to the active surface.

The average daily albedo for each site is 0.25 (site 1), 0.15 (site 2), 0.27 (site 3), 0.21 (site 4), and 0.18 (site 5). Sites 2 and 5 are the non-vegetated sites and also have the lower albedoes.

Emissivity

As described in a previous section, emissivity was determined indirectly by measuring longwave outgoing radiation and surface temperature. This is not a high precision technique, and thus differences from site to site can not be accurately determined.

Substrate Thermal Properties

Volumetric Heat Capacity

The formula for the heat capacity of any given layer is given by:

$$C = x_m C_m + x_g C_g + x_w + x_a C_a \qquad (4)$$

where C = total volumetric heat capacity,

x_m = volume fraction of solid matter and minerals,

C_m = volume heat capacity of solid and mineral matter (given the value 0.46cal/cm^3/°C by de Vries, 1958 and Kersten, 1949),

x_g = volume fraction of organic matter,

C_g = volume heat capacity of organic matter given the value 0.60cal/cm^3/°C by de Vries, 1958 and Kersten, 1949),

x_w = volume fraction of water

x_a = volume fraction of air,

C_a = volume heat capacity of air (given the value 0.0003cal/cm^3/°C by de Vries, 1958 and Kersten, 1949). This term is negligible.

The above expression reduces to:

$$C = x_m (0.46) + x_g (0.60) + x_w. \qquad (5)$$

The problem is to partition the volume fraction values for each of the sites in order to evaluate C for each site. From Figure 8, utilizing average x_w values from soil moisture observations, and making use of other field notes of the sites, Table 6 was constructed for each site of the volume fractions composing the respective active layers. From this information approximate values of C were obtained.

Thermal Diffusivity

Harder to observe and quantify are estimates of active layer thermal diffusivity. One approximate method, and the method used in this study, is to solve the following equation, under the assumption that the medium is a homogeneous solid (Sellers, 1968):

$$k_s = \frac{1}{2\omega}\left[\frac{(z_2 - z_1)^2}{\Delta t_{max}}\right] , \qquad (6)$$

where $\Delta t_{max} = t_{max(2)} - t_{max(1)}$,

TABLE 6

VOLUME FRACTIONS, HEAT CAPACITIES, THERMAL DIFFUSIVITIES, AND THERMAL CONDUCTIVITIES OF SITES

Station	Organic Matter[a]	Solid Matter[a]	x_w	t_{max} (hours)[b]	Thermal Diffusivity[c] (cm^2/sec)	Heat Capacity[d] ($cal/cm^3/°C$)	Thermal Conductivity[e] ($cal/cm/sec/°C$)
1	0.25	0.50	0.25	4.0	0.0034	0.61	0.0021
2	0.00	0.70	0.30	1.5[f]	0.0150[f]	0.72	0.0108[f]
3	0.20	0.60	0.20	3.0	0.0048	0.61	0.0029
4	0.58	0.24	0.18	5.0	0.0017	0.65	0.0011
5	0.00	0.90	0.10	2.0	0.0100	0.64	0.0064

[a] Calculated from Fig. 8 and field observations.

[b] Evaluated by equation (6).

[c] Evaluated by equation (6).

[d] Evaluated by equation (5).

[e] Evaluated by equation (7).

[f] Due to malfunction of -10 cm probe, a cited figure after Terzaghi (1952) is used for station 2.

where $t_{max(2)}$ = the time at which the maximum temperature is reached at level (2) (-10 cm) in the active layer,

$t_{max(1)}$ = the time at which the maximum temperature is reached at level (1) (the surface).

$z_2 - z_1$ = the depth difference between levels (1) and (2) (in cm),

ω = the angular frequency of oscillation (π /12 hours).

From selected diurnal periods with clear skies, estimates of k_s were obtained from the above equation and are given in Table 6.

Thermal Conductivity

Values of thermal conductivity are listed in Table 6 and were evaluated from:

$$\lambda = k_s C. \qquad (7)$$

The results show basically that the less organic matter in the active layer, the larger the conductivity.

Active Layer Depth

Depth-to-frozen ground was measured on a less frequent basis. For the periods of topoclimate observations, average active layer depths at the sites exceeded 50 cm at all sites. The average observation period depths were 55.0 cm (site 1), 70.0 cm (site 2), and no detectable frozen ground to the bedrock for all the other sites. It is suggested by Outcalt (1972a) that for tundra environments, active layer depths greater than the diurnal damping depth will have almost no

influence on the near-surface thermal regime. For analyses in this study, the influence of the active layer depth is considered nil during the diurnal thermal cycles investigated here. This, however, would not be a valid assumption for early and late portions of the field season at Chitistone Pass and for locations where there is a more shallow active layer in the pass.

Results of Transfer Variable Determinations

A summary of topographic, radiative, and thermal properties of the sites is given in Table 7 and will be used in the analysis as a guide in determining the relative importance of each in relation to active layer thermal regime behavior.

All sites have very similar sites horizons and active layer depths. This means that any thermal variations in the active layer from site to site can not be significantly explained by these factors. The data bank of thermal regime information in this study is viewed more in terms of the variations in slope, aspect, thermal diffusivity, heat capacity, thermal conductivity, and albedo from site to site.

TABLE 7

TOPOGRAPHIC, RADIATIVE, AND THERMAL PROPERTIES OF STUDY SITES

Site	(s) Slope	(a) Aspect	Albedo	C	x_w	k_s
1	nil	-	0.25	0.61	0.25	0.0034
2	nil	-	0.15	0.72	0.30	0.0150
3	23.0°	SE	0.27	0.61	0.20	0.0048
4	34.0°	SE	0.21	0.65	0.18	0.0017
5	28.0°	NW	0.18	0.64	0.10	0.0100

Site	λ	d	h	Other
1	0.0021	55.0	3	discontinuous mats of moss-lichen
2	0.0108	70.0	3	deltaic detritus material
3	0.0029	--	4	discontinuous mats of moss and willow with rocks on surface
4	0.0011	--	5	continuous mat of dryas and willow
5	0.0064	--	1	fine scree slope

Note: C is volumetric heat capacity.

x_w is volume fraction of water in the active layer.

k_s is thermal diffusivity.

λ is thermal conductivity.

d is active layer depth to frozen ground.

h is hours a site is obstructed by topography in relation to the solar elevation.

CHAPTER IV

DESCRIPTION OF THERMAL REGIMES AND THEIR RELATION TO TRANSFER VARIABLES

Introduction

The thermal regime data are divided into two groups for analysis. The first group is a mean period group; the second, a clear weather group. Mean period weather represents general weather conditions assumed to be the "normal weather" experienced at Chitistone Pass. Clear period weather represents a weather type which should promote maximum thermal contrasts across sloping terrain. Thermal regime data for the mean period consist of 21 diurnal periods based on hourly values. The appendices list data for temperature, albedo, emissivity, and radiation.

Mean Period Analysis of Thermal Regimes

The steps followed in determining the relative importance of topographic, thermal, and radiative properties in regulating surface and -10 cm thermal regimes are:

(1) a t-test for difference of means

(2) an F-test for homogeneous variances

(3) a Spearman's rho analysis of ranks of thermal regimes and site properties.

Table 8 lists calculations of means and variances of all six thermal regimes and mean Q_{max} (daily maximum solar radiation) for the mean period in 1967 and 1968.

Using means, variances, and standard errors, Tables 9-12 show significantly different means and variances of T_o regimes. A t-test and an F-test were employed to valuate convergence or divergence of regimes among site pairs.

It is concluded from Tables 9-12 that flat surface thermal regimes (sites 1 and 2) are not dissimilar in thermal behavior of surface temperature. These sites, however, have different thermal and radiative properties. This appears to be the product of a counter-balancing process between thermal diffusivity and albedo which tends to cause convergence of surface temperature behavior. Site 1 has a higher albedo, but a lower thermal diffusivity.

Together, sites 1 and 2 differ from sites 3 and 4 for T_{omax} and T_{or} (maximum and diurnal range of surface temperature). Mean diurnal surface temperature regimes ($\overline{T}_o$'s) are not dissimilar among the sites. Differences exist between sites 1 and 2, and 3 and 4 for T_{omax} and T_{or} and are traceable to different Q_{max} and Q_{tot} regimes (daily maximum and total solar radiation). This is highlighted directly by an F-test for homogeneous variances. The variance among the two flat sites and the two SE slope sites is homogeneous within these groups, but heterogeneous between the groups.

The only exception is the very strong overriding influence of albedo and thermal diffusivity on the site 5 thermal regime. Table 11 and 12 indicate that although radiation reception is comparable to sites

TABLE 8

MEANS AND VARIANCES OF THERMAL REGIMES AND Q_{max} [a]

Station	Year	T_{omax} (°C)	T_{or} (°C)	$\overline{T}_o$ (°C)	T_{-10max} (°C)	T_{-10r} (°C)	$\overline{T}_{-10}$ (°C)	Q_{max} (1y/min)
				Means				
1	1967	15.4	11.9	7.9	7.5	4.2	5.9	1.02
2	1967	15.8	12.0	8.4	--	--	--	1.02
3	1967	17.6	13.0	9.8	12.1	6.1	9.1	1.01
4	1967	21.4	18.3	9.3	9.3	3.9	7.4	1.12
1	1968	14.8	13.9	8.7	8.9	7.0	6.1	1.20
4	1968	20.0	14.9	11.5	10.7	5.4	8.6	1.27
1	1968	17.8	14.0	10.1	9.6	5.9	7.2	1.20
5	1968	20.8	16.1	11.3	11.1	6.3	8.3	1.19
4	1968	13.3	11.3	10.4	9.9	3.6	8.2	1.04
5	1968	17.1	16.5	9.1	9.5	5.6	6.9	0.97
				Variances				
1	1967	13.5	11.1	15.3	7.3	2.7	2.0	
2	1967	12.3	13.2	16.5	--	--	--	
3	1967	36.4	28.2	24.4	4.6	4.1	4.1	
4	1967	52.3	56.0	38.9	1.7	2.2	1.6	
1	1968	5.1	8.8	20.9	0.7	4.4	4.0	
4	1968	4.1	19.5	23.2	2.2	3.9	2.2	
1	1968	5.6	8.5	16.0	2.3	1.1	3.0	
5	1968	41.9	45.8	23.0	9.8	5.2	4.5	
4	1968	2.8	2.5	11.1	0.3	0.3	1.6	
5	1968	14.7	20.4	16.6	3.4	3.1	3.0	

[a] For the listing of the time periods of comparisons and dates see Table 3.

TABLE 9

SIGNIFICANTLY DIFFERENT SURFACE THERMAL REGIME MEANS (t Values) FOR 1967[a]

T_{omax}	1	2	3	4	5	T_{or}	1	2	3	4	5	$\overline{T}_o$	1	2	3	4	5
1	-	0.15	0.30	3.00*	na[b]		-	0.03	0.40	2.30*	na		-	0.10	0.25	0.40	na
2		-	0.50	2.20*	na			-	0.40	2.40*	na			-	0.20	0.12	na
3			-	0.50	na				-	0.80	na				-	0.09	na
4				-	na					-	na					--	na
5					-						-						-

[a]The matrix is tact values; rows and columns are station sites.

[b]Not applicable.

*The tact value is significant at the 0.05% level (Noether, 1971, 233).

TABLE 10

SIGNIFICANTLY DIFFERENT SURFACE THERMAL REGIME MEANS (t Values) FOR 1968[a]

T_{omax}	1	2	3	4	5	T_{or}	1	2	3	4	5	$\overline{T}_o$	1	2	3	4	5
1	-	na[b]	na	2.30*	0.50		-	na	na	0.50	0.30		-	na	na	0.40	0.10
2		-	na	na	na			-	na	na	na			-	na	na	na
3			-	na	na				-	na	na				-	na	na
4				-	2.50*					-	4.00*					-	0.30
5					-						-						-

[a]The matrix is tact values; rows and columns are station sites.

[b]Not applicable.

*The tact value is significant at the 0.05% level (Noether, 1971, 233).

TABLE 11

SIGNIFICANTLY DIFFERENT SURFACE THERMAL REGIME VARIANCES (F values) FOR 1967[a]

T_{omax}	1	2	3	4	5	T_{or}	1	2	3	4	5	$\overline{T}_o$	1	2	3	4	5
1	-	1.1	2.7*	3.9*	na[b]		-	1.2	2.5*	5.1*	na		-	1.5	9.6*	19.4*	na
2		-	2.9*	4.2*	na			-	2.1	4.2*	na			-	6.4*	12.8*	na
3			-	1.4	na				-	2.0	na				-	2.0	na
4				-	na					-	na					-	na
5					-						-						-

[a]The matrix is Fact values; rows and columns are station sites.

[b]Not applicable.

*The Fact value is significant at the 0.05% level (Noether, 1971, 234).

TABLE 12

SIGNIFICANTLY DIFFERENT SURFACE THERMAL REGIME VARIANCES (F Values) FOR 1968[a]

T_{omax}	1	2	3	4	5	T_{or}	1	2	3	4	5	$\overline{T}_o$	1	2	3	4	5
1	-	na	na	1.2	7.5*		-	na	na	2.3	6.4*		-	na	na	6.7*	8.8*
2		-	na	na	na			-	na	na	na			-	na	na	na
3			-	na	na				-	na	na				-	na	na
4				-	5.3*					-	8.2*					-	1.3
5					-						-						-

[a]The matrix is Fact values; rows and columns are station sites.

[b]Not applicable.

*The Fact value is significant at the 0.05% level (Noether, 1971, 234).

1 and 2 on site 5, surface thermal regimes are considerably different. Thus, together with the shallow nature of the weathered debris, low albedo, and moderately high thermal diffusivity, the thermal response at this site is larger for similar radiant heat loads than at sites 1 and 2. The importance of radiative and thermal properties increases for sites of this type. Topographic effects are diminished in importance.

The -10 cm regimes of T_{-10max} and $\overline{T}_{-10}$ (maximum and mean -10 cm temperature) tend to correspond with Q_{max} values, except for site 5 (for reasons cited above). The diurnal range of T_{-10} relates more to the magnitude of k_s. Higher k_s causes higher T_{-10r} values. The exception is site 3, which has the highest T_{-10r} regime, but not the highest k_s value. However, Q_{max} is very large for this site and tends to increase the value of T_{-10r}.

To summarize the relationships among the six thermal responses and the influencing site factors during mean or "normal" weather, a Spearman's rho rank correlation analysis was performed on the five sites. The scheme is to rank all sites in order of highest to lowest values of the six thermal regime categories and also for Q_{max}, Q_{tot}, C, k_s, x_w, and α. Table 13 gives the Spearman's rho rank correlation coefficient statistic (rs) for thermal responses and site variables.

For surface temperature regimes, the table indicates that without the site 5 anomaly cited before, Q_{max} and Q_{tot} have a very significant correlation with T_{omax} and T_{or} (the daily maximum and range of surface temperature). Also slightly significant is the soil water fraction. For subsurface temperatures, the only significant correlation is k_s with the T_{-10r}

TABLE 13

SPEARMAN'S RHO RANK CORRELATIONS OF THERMAL REGIMES VERSUS TRANSFER VARIABLES MEAN PERIOD[a]

	Q_{max}	Q_{tot}	C	k_s	x_w	α
T_{omax}	0.90[b]	0.90[b]	0.30	0.30	0.80	0.50
T_{or}	0.80	0.80	0.10	0.00	0.90	0.20
$\overline{T}_o$	0.40	0.40	0.30	0.20	0.50	0.60
T_{-10max}	0.40	0.40	0.70	0.20	0.70	0.70
T_{-10r}	0.60	0.60	0.40	0.90*	0.40	0.70
$\overline{T}_{-10}$	0.40	0.40	0.70	0.20	0.70	0.70

[a]The matrix of the table is Spearman's Rho Rank Correlation Coefficient (rs).

[b]If site 5 is eliminated, radiation has a highly significant rank correlation for the other sites.

*The rs value is significant at the 0.05% level (Siegel, 1956, 284).

regime (-10 cm daily range of temperature).

The general pattern of the rho values is for higher correlation between thermal/radiative properties and subsurface temperatures; and between topographic effects and soil water fraction and surface temperatures. The exception is site 5 for the latter.

Clear Period Analysis of Thermal Regimes

Mean period weather conditions listed in Table 3 indicate the predominance of cloudy, moist weather during sampling periods. This weather typifies the pass conditions during the summer season. However, for short-term clear weather periods, the question of magnitudes of site thermal regimes and their spatial variance has not been examined.

Theoretically, if topographic effects are of primary importance, these effects should manifest themselves during clear, calm weather. Table 14 and Figure 12 illustrate clear weather regimes. No statistical evaluation was performed on the data due to the lack of a sufficient number of clear periods for analysis. However, a rank correlation design can again be employed.

The thermal contrast between sites is enhanced during clear weather (see Table 14). From this table it is evident that the trend of thermal contrast is similar to the mean weather example, although the magnitude of the contrast change is non-linear. As slope (s) and aspect (a) change, the phase of the site thermal regimes are altered in an anticipated manner, with a pre-noon maximum for SE slopes and a late afternoon maximum at the NW slope site. Figure 12 shows there is a very strong correspondence between T_{omax} times and Q_{max} times. Again site 5

TABLE 14

CLEAR WEATHER SOLAR RADIATION AND ACTIVE LAYER THERMAL REGIMES

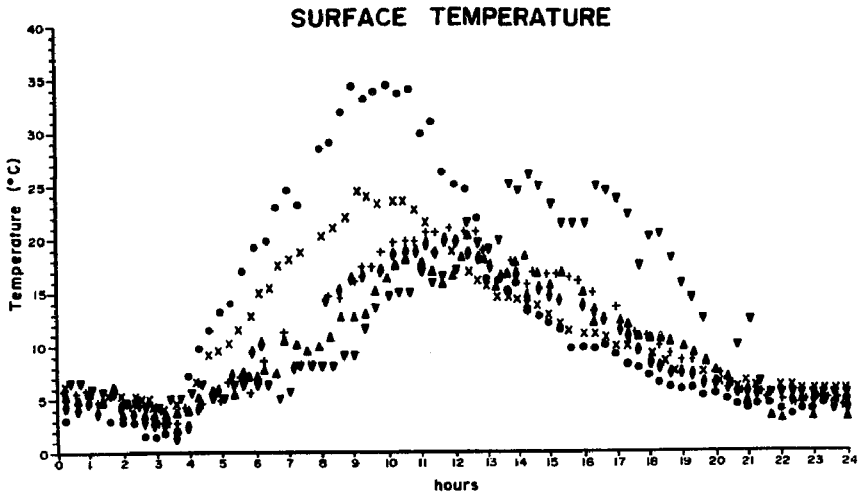
Station	Year	(1y/min) Q_{max}	(1y/day) Q_{tot}	(°C) T_{omax}	T_{or}	T_o	T_{-10max}	T_{-10r}	T_{-10}
1	1967[a]	1.150	555.0	19.1	17.6	10.0	10.1	5.6	7.2
2	1967	1.150	555.0	20.5	17.8	10.9	--	--	--
3	1967	1.310	593.0	23.0	19.0	11.6	15.5	9.3	10.5
4	1967	1.520	595.0	34.4	32.8	13.5	12.0	6.1	8.5
1	1968[b]	1.190	524.0	20.5	17.5	10.2	11.5	7.5	7.7
5	1968	1.150	453.0	29.3	25.3	12.1	15.3	9.8	9.8

[a]Stations 1, 2, 3, and 4 are for the 4th of August, 1967 (see Fig. 12).

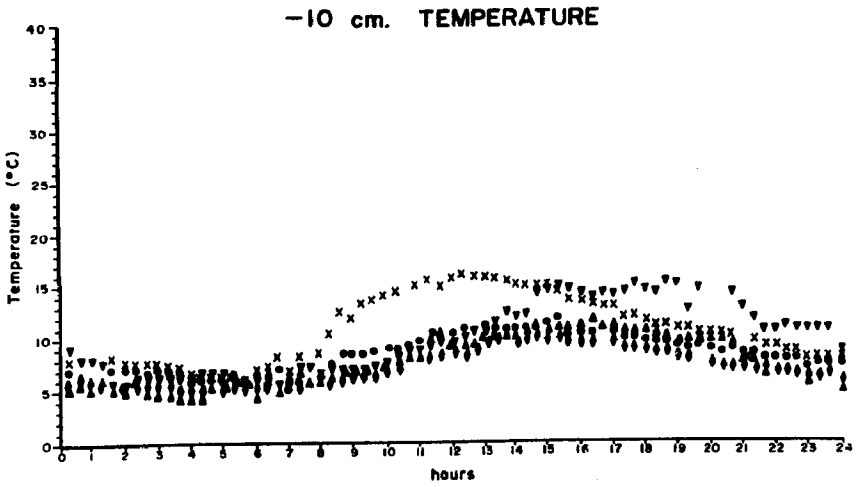
[b]Stations 1 and 5 are for the 21st July, 1968 (see Fig. 12).

Figure 12

Clear Period Thermal Regimes



STATION		DATE
1	♦	4 AUGUST, 1967
1	▲	21 JULY, 1968
2	+	4 AUGUST, 1967
3	×	4 AUGUST, 1967
4	•	4 AUGUST, 1967
5	▼	21 JULY, 1968



appears to be the anomaly in surface temperature regime magnitude, but does conform to the expected time of maximum surface heating. Table 15, showing Spearman's rho values in a similar way to Table 13, illustrates that (omitting the site 5 anomaly) Q_{max} and Q_{tot} are the only factors which individually control any thermal regime behavior pattern for the clear weather period.

The general pattern of rho values in Table 15 is similar to that for the mean period rank correlations. Some differences to be noted are:

(1) Q is more important for surface and -10 cm levels during clear weather,

(2) there is a generally lower set of rho values for thermal radiative properties for the -10 cm level during clear weather,

(3) there is a slightly higher set of rho values between surface temperature and thermal and radiative properties for the clear period.

Site Sensitivity to Thermal and Radiative Properties

Method of Analysis

In order to test the sensitivity of site thermal regimes to topographic, thermal, and radiative properties, an analysis was performed using clear and mean period weather thermal regime data. In this way, it is possible to evaluate the spatial variation of site thermal regimes (called "scale-up" of regimes) as a response to increases in solar heat loads at the surface produced by topographic, thermal or

TABLE 15

SPEARMAN'S RHO RANK CORRELATIONS OF THERMAL REGIMES VERSUS TRANSFER VARIABLES CLEAR PERIOD[a]

	Q_{max}	Q_{tot}	C	k_s	x_w	α
T_{omax}	0.90[b]	0.90[b]	0.30	0.30	0.80	0.50
T_{or}	0.90[b]	0.90[b]	0.30	0.30	0.80	0.50
$\overline{T}_o$	0.90[b]	0.90[b]	0.30	0.30	0.80	0.50
T_{-10max}	0.50	0.50	0.60	0.40	0.60	0.70
T_{-10r}	0.90*	0.90*	0.00	0.30	0.70	0.10
$\overline{T}_{-10}$	0.50	0.50	0.60	0.40	0.60	0.80

[a]The matrix of the table is Spearman's Rho Rank Correlation Coefficient (rs).

[b]If site 5 is eliminated, radiation has a highly significant rank correlation for the other sites.

*The rs value is significant at the 0.05% level (Siegel, 1956, 284).

radiative effects at the sites. To indicate the nature of the "scale-up" phenomena on sites, Table 16 lists the differences in thermal regime values between mean and clear weather. The difference values of the thermal regimes are not similar for all sites. This illustrates a non-linear scale-up from mean to clear weather periods. This scale-up is most obvious for surface temperature. To test further the original hypothesis, a test is performed to consider whether the non-linear scale-up phenomenon is due to topography or to the thermal/radiative properties of the sites.

To provide an insight to the answer, a regression analysis was performed on the site data, using T_o and T_{-10} regimes as dependent variables, and albedo and thermal diffusivity as independent variables. Six regression equations were analyzed using data from Tables 7, 8, and 9. The equations take the following forms:

$$T_{omax} = a' + b_{\alpha}\alpha + b_{k_s}k_s \quad (8)$$

$$T_{or} = a' + b_{\alpha}\alpha + b_{k_s}k_s \quad (9)$$

$$\overline{T}_o = a' + b_{\alpha}\alpha + b_{k_s}k_s \quad (10)$$

$$T_{-10max} = a' + b_{\alpha}\alpha + b_{k_s}k_s \quad (11)$$

$$T_{-10r} = a' + b_{\alpha}\alpha + b_{k_s}k_s \quad (12)$$

$$\overline{T}_{-10} = a' + b_{\alpha}\alpha + b_{k_s}k_s \; . \quad (13)$$

The relationships were evaluated for mean and clear periods separately. It is hypothesized that if the b coefficients are not significantly different, the thermal and radiative properties are not producing the non-linearity in the "scale-up" of thermal contrast among the sites. Rather,

TABLE 16

THERMAL REGIME DIFFERENCES FOR WEATHER CHANGES[a]

Station	$T_{omax(clear-mean)}$	$T_{or(clear-mean)}$	$\overline{T}_{o(clear-mean)}$
1	3.7	5.7	2.1
2	4.7	5.8	2.5
3	5.4	6.0	1.8
4	13.0	14.5	4.2
5	14.2	11.2	2.9

Station	$T_{-10max(clear-mean)}$	$T_{-10r(clear-mean)}$	$\overline{T}_{-10(clear-mean)}$
1	2.6	1.4	1.3
2	-	-	-
3	3.4	3.2	1.4
4	2.7	2.2	1.1
5	4.4	2.8	2.2

[a]Data for the construction of this table were taken from Tables 7 and 8.

slope and aspect are the major environmental factors which introduce the non-linear increase in site thermal contrast. This sensitivity testing procedure is similar to that discussed by Outcalt (1972b).

Results

Table 17 lists regression slope coefficients (b), partial correlation coefficients (r), standard errors of r (se), and the t-test scores from testing the significance of the b coefficients between clear and mean period weather (t^b). The extremely low values of the t^b's indicate the similarity in regression line slopes for both weather conditions, thus the low sensitivity of the "scale-up" of thermal regimes to thermal and radiative properties. The t^b albedo values are larger, but the correlation coefficients are very low. Conversely, the correlation coefficients for k_s are higher and more significant, but the t^b's are very small.

These results suggest that the influence of site thermal and radiative properties on site thermal regimes is rather insensitive to sky conditions and may in effect produce "background" thermal contrast upon which slope and exposure effects are additive during clear periods. As illustrated in the previous discussion, however, spatial variations in thermal regime behavior are also related to thermal and radiative properties (site 5 anomaly for example), but this spatial effect remains relatively constant due to its relative insensitivity to the sky condition. However, during periods of clear weather, site surface thermal/radiative property contrasts are completely overwhelmed by slope and aspect effects and will be detectable only when these variables are constant.

TABLE 17

THERMAL/RADIATIVE PROPERTY-THERMAL REGIME
REGRESSION ANALYSIS RESULTS

Regime	Weather	r_{α}	r_{k_s}	b^a_{α}	b_{k_s}	se_{α}	se_{k_s}
T_{omax}	clear	-0.17	-0.36	- 1.0	-0.3	0.43	0.39
	mean	0.20	-0.63	4.0	-1.0	0.43	0.27
T_{or}	clear	-0.16	-0.43	- 1.0	-1.0	0.45	0.32
	mean	-0.04	-0.54	- 1.0	-1.0	0.45	0.32
$\overline{T}_o$	clear	-0.11	-0.35	- 4.0	-1.0	0.44	0.39
	mean	0.30	-0.29	20.0	-2.0	0.41	0.41
T_{-10max}	clear	0.06	0.50	1.0	-0.7	0.49	0.38
	mean	0.49	-0.09	9.0	-0.1	0.38	0.49
T_{-10r}	clear	0.32	0.38	8.0	0.8	0.45	0.43
	mean	0.57	0.28	23.0	1.0	0.34	0.46
$\overline{T}_{-10}$	clear	0.14	0.38	4.0	0.9	0.49	0.43
	mean	0.36	0.01	11.0	0.0	0.44	0.50

Regime	t^b_{α} clear/mean	$t^b_{k_s}$ clear/mean
T_{omax}	0.10	0.01
T_{or}	0.00	0.01
$\overline{T}_o$	5.50	0.02
T_{-10max}	0.20	0.02
T_{-10r}	0.30	0.05
$\overline{T}_{-10}$	0.10	0.02

Note: All values are not significant at the 0.05% level.

[a] b coefficients are x 10^{-3}.

[b] tact values are x 10^{-1}.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Hypothesis Re-stated

The hypothesis re-stated is:

The effects of topography have an overriding influence on a site's thermal and radiative properties in rugged alpine terrain during high sun periods.

Results

The results of the Chitistone Pass investigation are:

(1) Topographic factors--slope and aspect--explain more of the spatial-temporal variations in active layer thermal regimes than the thermal and radiative properties of specific sites.

(2) Thermal and radiative properties are, however, important in fully explaining spatial variations in thermal regimes, but not in explaining the temporal scale-up variations of thermal regimes from cloudy to clear periods. These variables produce a "background" surface thermal contrast upon which the contrast produced by slope and aspect during beam radiation events is additive and frequently overwhelming.

(3) The relative ranking of geographic variables which control the clear weather thermal regime behavior is:

(a) slope and aspect,

(b) albedo, thermal diffusivity, and other site factors.

These basic results from a typical alpine/periglacial environment support the hypothesis. To more substantially investigate the topoclimate of alpine regions, remote sensing technology can be employed as long as interpreters consider the effect of topography on diurnal surface thermal regimes and develop strategies to remove these effects so that surface properties may be investigated.

Recommendations

A set of recommendations is given below specific to thermal imagery analysis in alpine/periglacial regions. This investigation highlights the necessity for the consideration of both surface thermal and radiative properties and topography in thermal map interpretation. These effects have not always been considered in remote sensing studies (see, for example, Mattsson, 1970). Specifically, the following steps are recommended:

(1) At the pre-flight stage, emphasis should be placed on preparing local maps of surface reflectivity, surface roughness length, and substrate physical properties over a selected series of test sites.

(2) An adequate map of local topography is essential.

(3) Before overflights are made, an analysis of the spatial variation of topography and thermal and radiative properties will enhance understanding of the expected thermal response of the terrain. This allows the investigator to interpret ground

conditions from the imagery and spatially extend his results away from the test sites.

(4) During the flights, the major ground truth information should consist of local weather data. Weather changes influence surface thermal responses; however, the thermal and radiative properties remain relatively constant with time.

(5) This investigation strongly indicates that the interpretation of thermal imagery acquired in mountain terrain is severely constrained by slope and exposure effects in clear weather. However, thermal mapping must be carried out in clear weather as cloud shadow images must be eliminated. Therefore, this thesis indicates that research efforts should be directed toward the application of spatial filtering techniques to remove the relatively low frequency effects of slope and aspect whilst enhancing the high frequency effects springing from surface geologic and ecological variations. It is these latter effects which yield information about ground conditions of importance to man in alpine areas, such as moisture availability, depth of the active layer, and vegetation distribution.

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APPENDIX I

THERMAL REGIME DATA

Blanks indicate no data available

Headings in table are site numbers

Table matrix is temperature in °C

Date	T_o					T_{-10}					T_{omax}				
1967	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
13 July	11.1	10.4	15.0	9.3		4.9	5.0	8.6	6.7		15.2	19.0	27.5	16.8	
14 July	9.1	10.3	17.3	10.9		5.4	5.4	10.2	7.3		23.5	13.0	30.5	21.0	
15 July	12.5			11.8		7.8			9.9		19.5			23.8	
22 July	7.8			8.8		5.1			5.6		14.3			19.5	
24 July	6.8			8.1		4.7			6.0		11.0			18.1	
30 July	8.1	8.8	8.5	8.0		6.4		9.1	7.4		14.4	14.5	13.5	15.8	
31 July	7.1	7.9	8.6	7.6		6.1		7.6	7.3		15.0	16.3	20.1	17.8	
1 Aug	7.3	6.8	8.2	8.4		5.2		8.7	7.1		15.1	14.1	13.5	16.0	
2 Aug	6.1	6.7	7.6	7.7		4.7		7.6	6.7		11.4	11.9	12.3	17.3	
3 Aug	8.9	9.8	10.4	10.6		6.5		9.3	7.7		18.5	20.8	18.8	36.0	
4 Aug	10.0	10.9	11.6	13.5		7.2		10.5	8.5		19.1	20.5	23.0	34.4	
5 Aug	7.8	8.5	8.3	8.4		6.2		8.6	7.6		13.3	13.9	11.6	14.5	
6 Aug	11.1	11.6	12.5	13.7		7.6		10.9	8.7		19.0	20.4	19.3	26.0	
7 Aug	10.7	11.5	13.6	14.5		8.0		12.1	9.5		19.5	21.3	22.8	33.4	
8 Aug	7.0	7.6	6.9	6.3		6.6		9.0	7.9		12.5	13.1	11.8	16.0	
9 Aug	6.0	6.3	7.3	6.9		5.1		8.3	6.9		13.5	14.8	15.5	20.3	
10 Aug	4.2	4.7	6.6	7.5		4.2		8.0	6.3		12.0	13.8	13.5	21.5	
11 Aug	4.6	4.9	4.8	5.5		3.9		7.3	6.2		9.3	10.0	9.8	14.5	
1968															
9 July				8.0	6.5				8.4	6.7				14.3	15.1
10 July				9.8	10.2				8.0	7.2				17.8	20.0
14 July	8.1			10.7		5.9			8.7		11.5			21.0	
15 July	6.8			11.3		5.2			9.0		16.6			22.3	
20 July	10.4				13.4	7.7				9.7	19.5				21.5
21 July	10.2				12.1	7.7				9.8	20.5				24.5
1 Aug	10.7			11.9	8.3	7.2			8.5	6.2	16.3			18.5	10.3
5 Aug	9.1			12.0	11.5	6.2			7.9	7.5	15.3			18.0	19.0

Date	T_o					T_{-10}					T_{omax}				
1967	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
13 July	7.7	13.3	20.5	12.3		6.8		10.0	8.0		4.3		2.5	3.0	
14 July	18.0	14.0	24.0	16.0		9.8		15.5	8.0		8.3		8.8	2.8	
15 July	15.3			19.8		9.5			11.0		3.8			3.0	
22 July	11.3			17.3		6.5			7.0		3.3			3.3	
24 July	9.5			17.6		6.5			7.0		3.3			3.3	
30 July	10.4	10.0	9.5	12.8		8.5		12.0	9.4		3.3		6.0	4.4	
31 July	11.0	12.3	14.6	13.8		8.5		10.3	8.5		4.0		7.8	2.3	
1 Aug	12.4	11.4	9.9	12.5		7.0		14.0	8.9		3.0		8.5	3.4	
2 Aug	7.4	8.7	7.3	13.8		6.9		9.5	8.5		3.4		4.8	3.0	
3 Aug	14.8	17.3	15.5	32.8		9.3		13.3	11.6		6.0		7.3	6.1	
4 Aug	17.6	17.8	19.0	32.8		10.1		15.5	12.0		5.6		9.3	6.8	
5 Aug	9.1	9.4	5.1	9.0		7.6		10.4	8.6		2.4		3.4	2.1	
6 Aug	14.0	14.9	12.5	20.3		10.5		13.5	10.0		5.5		6.0	3.5	
7 Aug	15.5	16.8	15.8	29.9		11.0		15.3	11.3		5.5		7.3	5.1	
8 Aug	9.5	9.6	5.3	14.3		8.0		10.3	9.0		2.9		3.8	3.5	
9 Aug	12.3	13.3	13.5	19.5		7.3		12.0	9.0		3.8		5.3	6.0	
10 Aug	11.8	12.9	13.5	21.8		5.8		11.0	8.4		2.8		6.5	4.9	
11 Aug	8.0	8.8	9.1	13.9		5.0		9.5	7.5		1.8		4.3	2.3	
1968															
9 July				14.3	15.1				9.8	13.0				10.3	8.8
10 July				17.8	20.0				13.8	18.0				10.3	11.3
14 July	11.5			21.0		15.0			17.5		9.5			11.8	
15 July	16.6			22.3		17.8			20.8		9.5			12.3	
20 July	19.5				21.5	15.8				16.0	10.3				12.3
21 July	20.5				24.5	17.5				20.3	11.5				15.0
1 Aug	16.3			18.5	10.3	10.0			11.5	5.8	8.8			10.0	7.3
5 Aug	15.3			18.0	19.0	13.1			10.0	13.0	8.3			9.0	9.5

APPENDIX II

SOLAR RADIATION DATA

Blanks indicate no data available

Headings in table are site numbers

Date	Q_{max} (lys/min) 1	2	3	4	5	Q_{tot} (lys/day) 1	2	3	4	5
1967										
13 July	1.19	1.19	1.64	1.48		644	644	675	675	
14 July	1.04	1.04	1.53	1.46		515	515	535	535	
15 July	1.22	1.22		1.43		583	583		608	
22 July	1.08	1.08		1.25		381	381		403	
24 July	1.17	1.17		1.20		307	307		317	
30 July	1.20	1.20	0.50	0.69		402	402	431	435	
31 July	1.10	1.10	0.99	1.03		347	347	367	370	
1 Aug	1.10	1.10	0.65	0.97		311	311	321	322	
2 Aug	0.80	0.80	0.54	0.42		298	298	300	300	
3 Aug	1.00	1.00	1.32	1.65		533	533	582	580	
4 Aug	1.15	1.15	1.31	1.52		555	555	593	593	
5 Aug	0.60	0.60	0.61	0.64		245	245	250	250	
6 Aug	0.70	0.70	0.91	0.84		393	393	415	416	
7 Aug	0.90	0.90	1.38	1.32		416	416	438	438	
8 Aug	0.90	0.90	0.89	0.99		295	296	300	300	
9 Aug	1.05	1.05	0.63	1.26		447	447	469	470	
10 Aug	1.00	1.00	0.92	1.23		425	425	447	447	
11 Aug	1.10	1.10	1.34	0.74		348	348	368	368	
1968										
9 July				1.10	0.61				593	447
10 July				0.66	0.73				509	401
14 July	1.20			1.53		648			679	
15 July	1.20			1.15		559			585	
20 July	1.19				0.49	524				462
21 July	1.20				1.15	535				453
1 Aug	1.25			1.30	0.71	537			575	458
5 Aug	1.15			1.11	0.82	444			467	387

APPENDIX III

ALBEDO DATA

Blanks indicate no data available

Headings in table are site numbers

Table matrix is albedo as a decimal

Date	Noon Albedo 1	2	3	4	5
1967					
13 July					
14 July					
15 July					
22 July					
24 July					
30 July	0.25	0.14	0.23	0.16	
31 July	0.44	0.30	0.26	0.18	
1 Aug	0.20	0.13	0.27	0.14	
2 Aug	0.23	0.07	0.31	0.19	
3 Aug	0.22	0.16	0.33	0.20	
4 Aug	0.24	0.14	0.24	0.21	
5 Aug	0.23	0.12	0.25	0.27	
6 Aug	0.24	0.12	0.27	0.21	
7 Aug	0.22	0.14	0.28	0.24	
8 Aug	0.21	0.13	0.31	0.20	
9 Aug	0.22	0.10	0.28	0.22	
10 Aug	0.22	0.11	0.29	0.21	
11 Aug	0.25	0.20	0.27	0.20	
1968					
9 July				0.24	0.18
10 July				0.24	0.16
14 July	0.20			0.25	
15 July	0.20			0.27	
20 July	0.16				0.05
21 July	0.30				0.18
1 Aug	0.21			0.26	0.15
5 Aug	0.22			0.23	0.28

APPENDIX IV

EMISSIVITY DATA

Blanks indicate no data available

Headings in table are site numbers

See text for derivation explanation

Date	Emissivity 1	2	3	4	5
1967					
13 July					
14 July					
15 July					
22 July					
24 July					
30 July	0.98			1.00	
31 July	0.99				
1 Aug	1.00				
2 Aug	1.00			1.00	
3 Aug	0.98			0.98	
4 Aug	0.99			0.99	
5 Aug	1.00			0.99	
6 Aug	0.95			1.00	
7 Aug	0.93			0.90	
8 Aug	0.99			0.98	
9 Aug	0.99			0.90	
10 Aug	0.99			1.00	
11 Aug	1.00			1.00	
1968					
9 July				0.93	0.96
10 July				0.97	0.89
14 July	0.96			0.92	
15 July	0.99			0.97	
20 July	0.94				1.00
21 July	0.90				0.95
1 Aug	0.90			0.95	0.95
5 Aug	0.99			0.95	0.90