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THE SIGNIFICANCE OF FROST ACTION
AND SURFACE SOIL CHARACTERISTICS TO WIND
EROSION AT ROCKY FLATS, COLORADO

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Third Progress Report

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ABSTRACT

This report summarizes information on soil frost effects collected on Rocky Flats during the 1976-1977 winter. The work has continued on two scales as in the previous two winters.

On a broad scale, empirical surveys along 4 line transects during the second half of the winter support earlier conclusions that the frost susceptibility of the Rocky Flats soils is well keyed to topography. This has been used in testing a mapping procedure for potential soil frost activity in the entire Rocky Flats area.

On a site scale, instrumental records of weather and soil conditions have been maintained throughout the winter at the Lindsay Ranch study site, northwest of the Rocky Flats Plant. During the winter, 9 frost heave events have been recorded and are described here. This represents a low frequency of soil disturbance by frost and is accounted for by the drought conditions on the Colorado Piedmont during 1976-1977. Even the events which occurred were of relatively slight magnitude, a further reflection of the lack of soil moisture during the period.

The 1976-1977 winter was the final period of intensive field observation in this project. A final report, to include synthesis of 2½ winters of observation, is now in the planning stage.

INTRODUCTION

This is the third progress report of research into needle ice growth, soil surface changes and wind erosion at Rocky Flats, Colorado. It reports results from the second complete winter in which records have been maintained on the study site at the Lindsay Ranch and includes the results of empirical surveys of frost effects made during 1977. This report is largely descriptive in nature and is intended to be followed by a comprehensive analysis of the entire study period in a final report of the project.

The problem under study was defined in the second progress report (Caine & Morin 1976) and so need not be repeated in detail here. In essence, the study concerns the evaluation of the interactions between soil freezing (particularly that associated with needle ice development) and the consequent erosion of soil by the wind. Such an interaction may be responsible for plutonium resuspension from contaminated soil.

As in the previous winter, a detailed program of field observation was carried out at the Lindsay Ranch site on Rocky Flats during 1976-1977. The other observational effort has involved a spatial analysis of the evidence of soil frost activity on the ground. This was intended as a verification of the indirect mapping procedures defined by earlier work (Caine & Morin 1976).

Calendar

Detailed records from the environmental recording system at the Lindsay Ranch are available for almost all of the period covered by this

report. This program of observation was terminated on May 3, 1977 when the instrumentation was removed to Boulder for routine maintenance. Table 1 provides a summary of the instrumentation and period of observation from which this record is derived.

Personnel

The following personnel have worked on this project in the period October 1976 - June 1977:

Nel Caine	Principal Investigator	15% time
John Clark	Instrumentation Tech.	$\frac{1}{2}$ month
Margaret Eccles	Data Analyst	month
Pierre Morin	Research Assistant	50% time
Clifton Mitchell	Undergraduate Assistant	25% time
Robin Nicholas	Research Assistant	25% time

In addition, approximately 10 man-days of technician time in the Electronics Shop, Physics Department, University of Colorado were expended in maintenance and calibration of field instrumentation.

This Report

The body of this progress report follows a pattern similar to that of two earlier reports from this project (Caine & Morin 1975; 1976). It consists of two parts each concerned with a different approach to the study of soil frost effects: studies on a wide spatial scale involving the entire Rocky Flats area, and detailed studies from the Lindsay Ranch site. Recent work on both of these lines has tended to support the conclusions reached earlier.

TABLE 1

INSTRUMENTATION AND CALENDAR OF OBSERVATIONS:

1976 - 1977: Continuous Recordings

<u>DATA</u>	<u>DATES</u>	<u>PRECISION</u>
Air Temperature 2 m	1-1-76 to Present	± 1 degree C
Air Humidity 2 m	1-1-76 to Present	± 3%
Precipitations	1-1-76 to Present	± 1 mm
Soil Temperatures :		
Depth 0 cm	1-1-76 to 5-3-77	± 0.25 degrees C
2 cm	1-1-76 to 12-1-76	"
5 cm	1-1-76 to 5-3-77	"
15 cm	12-13-76 to 5-3-77	"
Air Temperature 15 cm	1-1-76 to 5-3-77	"
Soil Heave	1-1-76 to 5-3-77	± 0.2 mm
Net Radiation	4-7-76 to 5-3-77	± 0.05 ly/mm
Wind Speed 3 m	1-1-76 to 5-3-77	± 1 mph
Wind Speed 0.5 m	1-1-76 to 5-3-77	"
Wind Direction 3 m	1-1-76 to 5-3-77	± 20 degrees

Note: Due to instruments failures some short periods of data can be missing.

1976 - 1977: Discontinuous Recordings

From January 20, 1976, to Present:

- Soil Moisture and Temperature at 5, 10 and 20 cm deep at sites B, D and F.
- Soil Temperatures at 2, 5, 10 and 20 cm deep at site B and at 10 and 20 cm deep at sites D and F.

BROAD SCALE STUDIES

Two sub-programs were originally included under this heading: one involving the study of past weather records from the Rocky Flats area and one a larger spatial scale that of the detailed study site at the Lindsay Ranch. No work has been done on the first of these in 1976-1977. The second sub-program has been pursued along empirical lines during the latter half of the 1976-1977 winter by repeated field surveys for evidence of soil frost activity. This observational program was undertaken to provide a test of the theoretical model for the distribution of frost action on Rocky Flats (Caine & Morin 1976).

Procedures

Field observations were made at marked stations on four transects, one at each corner of the inner buffer zone at the Rocky Flats Plant site. Each transect was located qualitatively so as to intersect a cross section of the environments of the buffer zone and was surveyed on the ground on a weekly (or shorter) interval during the last three winter months of 1976-1977. The lack of a record for the period prior to January 1977 is probably not serious since the record from the Lindsay Ranch shows little frost action in the early part of the winter (below).

At each station, the area within 5 m of the station was examined for evidence of soil disturbance by frost heave and a four-part scale used to describe the observed condition of the soil surface. These observations were made by the same observer on all occasions and were based upon criteria requiring visible effects at the soil surface (Table 2). The absence of such visible evidence does not mean per se the absence of soil

TABLE 2

SCALE OF FROST EVIDENCE ON SOIL:

- 0... No apparent evidence of frost heave.
- 1... Weak surface evidence of needle-ice represented by minor or absent heave of gravel, minor soil cracks along the surface or around rocks, slight development of an undulating surface, and / or loosened soil.
- 2... Moderate surface evidence of needle-ice represented by visible displacement of rocks and soil, weak to moderate undulating surface, and / or loosened soil.
- 3... Strong surface evidence of needle-ice represented by significant development of soil cracks along the surface and around rocks, well developed undulating surface, and loosened soil.

freezing but it is reasonable to suggest an insignificant contribution to eolian erosion.

Results

Statistical analysis of these data has not yet been completed but the tabulated summaries included here show a pattern of variation that is consistent with the soil textural studies reported earlier (Caine & Morin 1976). This is evident in spite of a short period of record and the fact that a lack of precipitation in 1976-1977 seems to have reduced the efficacy of needle ice activity in that winter.

Table 3 summarizes the observational results with respect to four important environmental conditions at each station. A high level of interaction between these four characteristics is clearly evident but has not yet been evaluated statistically. Here, we offer only a few comments about the effect of each environmental characteristic separately, i.e. ignoring the interactions.

Topography. Table 4 shows a good correspondence between the three topographic situations defined earlier (Caine & Morin 1976) and the field evidence of soil disturbance by segregation ice. The interfluvies of Rocky Flats are the preferred zones for frost action, the valley floors are areas of little effective frost, and the valley sides show an intermediate susceptibility to frost.

Lithology. A clear correspondence is also evident between the frequency of observed evidence of frost action and the lithological environment of each station (following Hurr 1976). Most evidence of frost influences are

OBSERVED EVIDENCE OF FROST ACTION AND

ENVIRONMENTAL CONDITIONS:

<u>ENVIRONMENTAL</u>		<u>STRENGTH OF EVIDENCE</u>		
<u>CHARACTERISTIC</u>		STRONG	MODERATE	NONE
Topography.....	Interfluve.....	Valley-side.....	Valley-floor	
Lithology.....	Rocky Flats..... Alluvium	U. Laramie..... Formation		
Soils.....	Gravelly and cobbly soils	Deep clay..... Soils	Argiustolls	
Vegetation.....	Dry..... Communities	Moist..... Communities	Wet Communities	

TABLE 3

TOPOGRAPHIC INFLUENCES ON FROST ACTION: ROCKY FLATS

<u>FROST RATING</u>	<u>TOPOGRAPHIC SITUATION</u>		
	Interfluvial:	Valley-side:	Valley-floor:
0	7	7	33
1	0	34	33
2	0	34	0
3	93	24	33

NOTE: The frost rating scale is defined in Table 2 ; All values in the table are percentages.

TABLE 4

LITHOLOGIC INFLUENCES ON FROST ACTION: ROCKY FLATS

<u>FROST RATING</u>	<u>LITHOLOGY</u>		
	Rocky Flats Alluvium:	Arapahoe Formation:	U. Laramie Formation:
0	9.5	6	14
1	9.5	38	29
2	5	38	29
3	76	19	29

NOTE: The frost rating scale is defined in Table 2 ; All values in the table are percentages.

TABLE 5

found on the Rocky Flats Alluvium with apparently less activity on the Cretaceous materials (shales and sandstones) of the Arapahoe and Laramie Formations (Table 5). This influence is one that is obviously confounded with topographic position in that the interfluvial areas are also the situations underlain by the Rocky Flats Alluvium.

Soils. The soils mapped by Illsley & Amen (1974) have been grouped into three broad categories for purposes of this analysis (a number of other categories could be defined but are spatially unimportant). Deep, well-drained gravelly soils (Nederland sandy loam and Valmont clay loam) correspond to situations of most frost activity (Table 6) but also correspond to topographically high situations underlain by the Rocky Flats Alluvium. The deep clay loams and the more poorly drained clays and loams of the valley sides and floors, in contrast, show less evidence of frost influence. A fourth soil type (not shown in Table 6 because few observation stations were located on it) includes the well-drained alluvial soils along the creeks at Rocky Flats. These show wide variability in their intensity of response to frost action.

Vegetation. A preliminary analysis of the frequency of observed frost influences under different vegetation units (as mapped by Clark & Webber 1975) matches the distribution pattern defined by other environmental characteristics (Table 7). The variety of dry vegetative units that are characteristic of the interfluvial situations on Rocky Flats correspond to a high level of frost activity while the moist communities on the transects show a greater level of variability in the recorded response to frost action. The wet environments along stream channels and in marsh areas

SOIL - TYPE INFLUENCES ON FROST ACTION : ROCKY FLATS

FROST RATING:

SOIL CHARACTERISTICS:

	Gravelly Soils (A)	Deep, Clay Soils (B)	Wet Soils (C)
0	13	5	20
1	17	31	40
2	4	42	20
3	65	21	20

(A) : Nederland gravelly sandy loam & Valmont gravelly clay loam.

(B) : Denver-Kutch-Midway soils & Nunn and Denver clay loam.

(C) : Poorly drained clay and loam Argiustolls.

TABLE 6

VEGETATION INFLUENCE ON FROST ACTION : ROCKY FLATS

FROST RATING:

VEGETATION COMMUNITY TYPE:

	Dry Prairie, Pasture, Barrens	Moist Meadow and Scrub
0	0	9
1	14	35
2	14	30
3	73	26

NOTE: The frost rating scale is defined in Table 2 ; All values are percentages.

TABLE 7

are represented by only three stations and so are not included in Table 7. All three of these stations failed to yield any visible evidence of surface changes due to soil freezing.

Discussion

It is apparent that the surface evidence of soil freezing at Rocky Flats corresponds to environmental characteristics in a relatively simple manner (Table 3). Soil surface modification by needle ice occurs preferentially on the flat interfluvial areas which have gravelly soils developed on the Rocky Flats Alluvium and a xeric (and thus discontinuous in places) vegetation cover. Along the valley sides, under a more mesic vegetation, the evidence of needle ice activity is more variable in distribution and less well developed. This appears to reflect a more continuous vegetation cover and a greater variability in soil moisture conditions. Finally, there is little empirical evidence of needle ice development in the soils of the valley floors, except locally along stream channel banks.

This pattern of observations corroborates the conclusions reached earlier in this inquiry about the probable frost susceptibility of the Rocky Flats soils. Caine & Morin (1975) suggested the same spatial pattern on the basis of soil textural analysis and the theory of segregation ice development in soil. It is pleasing that the observational record (albeit a short one) matches the theory and it adds to the confidence in the mapping procedure outlined in the earlier report.

SITE STUDIES

Detailed recording of needle ice and frost heave occurrence continued during the 1976-1977 winter on the study site at the Lindsay Ranch, in the northwestern part of the buffer zone around the Rocky Flats Plant. The recording system and instrumentation had been maintained in the field during the 1976 summer and so an almost continuous record is available for the entire winter (Table 1). The environmental characteristics measured are the same as those recorded during the previous winter.

The winter of 1976-1977 was an unusually dry one along the east side of the Colorado Front Range and this is reflected in the record of frost heave events at Rocky Flats. Only 9 heave events of any significance (more than 1 mm of soil surface lifting) were recorded in the entire winter, most of those occurring in the latter part of the winter. By contrast, 26 heave events were instrumentally recorded in the previous winter and on a further 7 occasions needle ice development was observed on the site but not recorded. The temporal pattern of recorded heave events matches that found in earlier winters, although in the period under review it involves a concentration in the late-winter and early spring with no activity during the fall.

As a background to the occurrence of the nine heave events, daily maximum and minimum values for air relative humidity, air temperature at 2 m, air temperature at 15 cm, soil-air interface temperature and total daily precipitation are plotted on Figure 1. Mean daily values for the three temperatures and for relative humidity appear on Figure 2 Table 8 presents a statistical summary for each parameter over the 200 days period (from October 8, 1976 to April 4, 1977).

TABLE 8

DATA DESCRIPTION FOR THE 1976 - 1977 WINTER:

DATA:	MEAN:	S.D	S.E OF MEAN:	MAXIMUM:	MINIMUM:	RANGE:
Max Air Temp:	10.4	6.9	.49	26.	-7	33
Min Air Temp:	-4.6	5.9	.41	8	-24	32.
Max If Temp:	18.4	10.2	.72	40.	-1	41
Min If Temp:	-2.7	4.2	.30	10.	-13	23
Max Scr Temp:	8.6	6.8	.48	25	-13.	38
Min Scr Temp:	-3.4	6.0	.43	11	-22	33
Max Rel Hum :	81%	26.1	1.84	100%	15%	85%
Min Rel Hum :	32%	20.8	1.47	100%	7%	93%
Precipitations:	.42	1.5	.11	11	0	11.

UNITS: All the temperatures are in degrees Celcius
The relative humidities are in percent
The precipitations are in 1:20' ch. of inches

ABBREVIATIONS : Max= Maximum , Min= Minimum .
Air temp= Air temperature measured at 15 cm above ground .
If temp= Interface temperature .
Scr temp= Air temperature measured in instrument screen (2m) .
Rel Hum = Air relative humidity in instrument screen.
S.D = standard deviation.
S.E = standard error..

NOTE : Individual values are daily minimas and maximas for a 200 days
period from 1976 10 8 to 1977 4 25 .

The mean maximum interface temperature (18.4 degrees C) is a full ten degrees warmer than the mean maximum air temperature at 15 cm above ground. The warmest temperature of the record was 40 degrees C at the interface, the coldest is -24 degrees C at 15 cm above ground. Absolute temperature ranges are 50 degrees C (15 cm above ground), 53 degrees C (interface) and 47 degrees C (shelter). The maximum daily precipitation recorded was 0.55 inches and the daily mean precipitation is only 2 hundredths of an inch. The means for daily relative humidity varied between 32% (minimum) and 81% (maximum).

Soil temperatures

Discontinuous measurements of soil temperatures were made during the 1976-1977 winter at 3 sites: B, D, and F (for site locations, see Caine and Morin 1975). The measurements were made with Yellow Spring Instruments thermistors (composite #44018) that remained undisturbed during the period of observation. The thermistor were buried at depths of 2, 5, 10, and 20 cm at site B; and of 10 and 20 cm at sites D and F. During the period of August 26, 1976 to April 28, 1977, 56 measurements were made.

Table 9 presents a statistical summary of the 56 observations. As was noted in the two preceeding reports, site D, located on the south-facing slope, is markedly warmer than sites B and F. The mean soil temperature at 20 cm deep at site D is almost the same as it is at 2 cm deep at site B: the role of exposition is evident. The absolute maximum soil temperature recorded at the Lindsay Farm site was recorded at 10 cm deep at site D (91 degrees F, on 9-3-76); on this period of very warm soil temperatures, sites D and F both indicate a much greater penetration

TABLE 9

DATA DESCRIPTION FOR 56 SOIL TEMPERATURE MEASUREMENTS AT 3 SITES :

<u>SITE:</u>	<u>MEAN:</u>	<u>S.D:</u>	<u>S.E. of MEAN:</u>	<u>MAXIMUM:</u>	<u>MINIMUM:</u>	<u>RANGE:</u>
B -2cm	49.8	14.2	1.9	89.5	34.0	55.5
B -5cm	47.0	12.4	1.7	83.0	34.0	49.0
B -10cm	45.0	10.9	1.5	77.0	34.0	43.0
B -20cm	44.6	10.0	1.3	74.0	35.0	39.0
D -10cm	53.3	12.8	1.7	91.0	39.0	52.0
D -20cm	49.6	10.5	1.4	80.0	38.0	42.0
F -10cm	46.2	14.4	1.9	87.0	32.0	55.0
F -20cm	42.5	10.3	1.4	74.0	31.0	43.0

NOTE: All temperature values are expressed in degrees Fahrenheit, the 56 measurements were made during the period from 76-8-26 to 77-4-28 .

of heat in the ground than site B. The absolute minimum temperatures indicate that site F is the coldest and site D the warmest; it is interesting to note that the coldest soil temperature on record for those measurements was observed at 20 cm deep at site F (31 degrees F on 12-21-76). Those cold temperatures in the valley floors at Rocky Flats were reported earlier (Caine & Morin 1975, 1976) and also observed this year by Nicholas (Nicholas 1977), they are believed to result from different soil moisture conditions and textures and from differences in vegetation (on calm nights some orographic influences could be noticeable).

The ranges of temperatures vary from a maxima of 55.5 degrees F at -2 cm, site B, to 39 degrees F at -20 cm, site B. As is to be expected, the ranges of observed temperatures decrease with depth.

The mean gradients of soil temperatures are represented on Figure 3. The gradients for site B are strong in the first 10 cm (an average of 0.66 degrees F/cm) and very weak at depth (only 0.04 degrees F/cm between 10 and 20 cm). Sites D and F have the same temperature gradient between 10 and 20 cm (0.37 degrees F/cm). The soil temperature gradients indicate that site B is more isothermal at depth than sites D and F. The 56 temperature measurements at 20 cm deep for sites B, D, and F are plotted on Figures 4 and 5 for a period going from 8-26-76 to 4-28-77. The depth of 20 cm was retained for the figures in order to limit the short term fluctuations. Several facts are worth noting on Figures 4 and 5; the classification of the 3 sites in function of soil temperatures is evident and last during the all period; the drop in soil temperatures for the winter is very clear (on the average, the monthly soil temperatures at 20 cm were 67 degrees F

FIGURE 3

MEAN SOIL TEMPERATURE GRADIENTS FOR 56 MEASUREMENTS AT 3 SITES :

FIGURE 5

in September, 53°F in October, 44°F in November, 38°F in December, 36°F in January, 39°F in February, 42°F in March and 48°F in April); even at 20 cm deep soil temperatures can fluctuate rapidly, especially at site D; as indicated by the arrows on Figures 4 and 5, the occurrence of heave events does not coincide to any particular temperature pattern at this depth; no heave event was, however, recorded during the coldest period (January and early February). The broad classification of the Lindsay site into Interfluvial, Valley-Sides and Valley-Floors (Caine & Morin 1976) reappears clearly in the distribution of soil temperatures this winter and must be compared to the observations of Nicholas (1977).

Heave Records

The general characteristics of the 9 heave events for which records are available are summarized in Table 10. This confirms the impression that dry soil conditions limited the effectiveness of frost action in 1976-1977: the mean heave for the 9 events is 3 mm (cf 5.2 mm and 5.5 mm in 1975-1976 and 1974-1975 respectively). It should be remembered, of course, that the recorded magnitude of heave underestimates the actual magnitude by an unknown amount: the resistance of the sensor to vertical movement ensures that. The temporal pattern of heave follows that established in earlier reports of this project (Caine & Morin 1975, 1976) and by the work of others (Outcalt 1970, 1971; Fahey 1974). A slow rate of lifting of the soil surface throughout the night peaks at about 0700 hrs. and is followed by a more rapid falling back of the soil surface as ice needles ablate and the mass of the heave sensor forces collapse of the soil surface.

TABLE 10

DATE	MEAN	SD	MAX	MIN	RANGE	DATE	MEAN	SD	MAX	MIN	RANGE
76 11 14-15						77 3 10-11					
HEAVE	.6	.3	1.0	0.0	1.0	HEAVE	1.7	1.4	4.1	0.0	4.1
W SP .5	2.1	.9	4.0	0.0	4.0	W SP .5	7.8	3.6	14.0	2.0	12.0
W SP 3	7.0	2.7	15.0	3.0	12.0	W SP 3	22.2	8.6	37.0	7.0	30.0
AIR T	.7	5.4	9.0	-6.0	15.0	AIR T	-1.1	1.2	1.0	-3.0	4.0
IF T	2.1	4.4	11.0	-2.0	13.0	IF T	.2	.4	1.0	0.0	1.0
SOIL T	3.0	1.4	6.0	1.0	5.0	SOIL T	1.3	.5	2.0	1.0	1.0
76 12 11-12						77 3 11-12					
HEAVE	.5	.5	1.3	0.0	1.3	HEAVE	2.2	1.4	4.0	.7	3.3
W SP .5	2.5	1.2	4.0	0.0	4.0	W SP .5	3.5	2.6	9.0	0.0	9.0
W SP 3	7.4	4.4	16.0	0.0	16.0	W SP 3	11.7	6.0	25.0	3.0	22.0
AIR T	1.8	3.0	6.0	-3.0	9.0	AIR T	3.3	5.3	12.0	-2.0	14.0
IF T	1.1	4.6	11.0	-3.0	14.0	IF T	3.6	8.2	21.0	-2.0	23.0
SOIL T	1.7	.7	3.0	1.0	2.0	SOIL T	2.6	3.5	9.0	0.0	9.0
76 12 14-15						77 3 12-13					
HEAVE	1.1	.5	1.8	.3	1.5	HEAVE	1.1	.6	2.5	.5	2.0
W SP .5	2.7	1.0	4.0	1.0	3.0	W SP .5	1.9	1.6	6.0	0.0	6.0
W SP 3	6.0	2.6	12.0	3.0	9.0	W SP 3	6.7	4.9	20.0	0.0	20.0
AIR T	4.1	4.0	11.0	-2.0	13.0	AIR T	8.0	8.0	21.0	-1.0	22.0
IF T	2.6	8.9	22.0	-5.0	27.0	IF T	8.7	13.3	33.0	-4.0	37.0
SOIL T	2.5	1.4	5.0	1.0	4.0	SOIL T	5.0	4.0	12.0	1.0	11.0
77 2 14-15						77 4 4-5					
HEAVE	1.9	2.3	6.5	0.0	6.5	HEAVE	1.3	1.1	4.3	0.0	4.3
W SP .5	1.3	.8	2.0	0.0	2.0	W SP .5	2.9	.8	5.0	2.0	3.0
W SP 3	6.0	2.5	9.0	0.0	9.0	W SP 3	7.3	2.9	12.0	3.0	9.0
AIR T	-2.0	6.4	9.0	-10.0	19.0	AIR T	5.5	5.2	14.0	-1.0	15.0
IF T	1.9	3.4	10.0	-1.0	11.0	IF T	7.3	9.5	25.0	-2.0	27.0
SOIL T	1.9	1.5	5.0	1.0	4.0	SOIL T	4.3	3.9	11.0	1.0	10.0
77 3 7-8											
HEAVE	.2	.4	1.5	0.0	1.5						
W SP .5	3.5	2.2	8.0	1.0	7.0						
W SP 3	12.5	6.8	28.0	6.0	22.0						
AIR T	9.7	5.3	18.0	2.0	16.0						
IF T	8.4	10.4	27.0	-2.0	29.0						
SOIL T	4.0	3.3	10.0	1.0	9.0						

ABBREVIATIONS: AIR T = air temperature at 15cm above ground
 IF T = interface temperature (0cm)
 SOIL T = soil temperature at 5cm deep

UNITS: HEAVE = mm.
 WIND SPEEDS = mph.
 TEMPERATURES = degrees Celsius.

ABBREVIATIONS: SD = standard deviation
 MAX = maximum
 MIN = minimum
 W SP .5 = wind speed at 0.5 meters
 W SP 3 = wind speed at 3 meters

Air and surface temperatures show the expected variations associated with needle ice growth. Freezing, but not extremely low, temperatures are associated with ice needle growth: the lowest air temperature recorded during a heave event was one of -10°C (at 15 cm height) on February 14-15. Figure 6 suggests that it may be possible to differentiate two types of heave event in terms of temperature. Events 5, 8 and 9 seem to have been associated with warmer conditions than the other six of the winter. Such a differentiation has not yet been tested on the larger sample of heave events from the two preceding winters.

In other respects, our records continue to contradict the findings of other researchers. In 1976-1977 as in the previous two winters, surface heave and needle ice development have been found to occur under relatively windy conditions. In all 9 events but one, wind speeds in excess of 10 mph were recorded; during 4 events, wind speed exceeded 20 mph (at 3 m above ground surface). This conflict with the results of other workers may derive from the characteristics of the Lindsay Ranch site - a high roughness coefficient suggests that needle ice development occurs well below the level of no air movement. The intermittent vegetation cover on the site may, therefore, facilitate needle ice growth (by comparison to completely open situations) during windy periods.

Heave Events

In this section of the report, the 9 recorded frost heave events of the 1976-1977 winter are described in a manner similar to that used in previous reports.

MEAN OF HOURLY VALUES FOR NINE HEAVE EVENTS :

FIGURE 6

Event 1, November 14-15 (Figure 7). The first event of the winter is typical of the more common, low-amplitude frost heave events at Rocky Flats. It involves little soil moisture, relatively constant temperature conditions, low total heave and slow heave rates (in this case, 0.16 mm hr^{-1} on average).

After a 17 day drought, 1 mm of precipitation fell during the day preceding the first heave of the winter. During the previous 3 days, temperatures had fallen but then had risen slightly with the precipitation of November 14: at the start of the event, the soil temperature was 2°C , the soil surface 1°C and the air temperature -2°C . Wind velocities were low and increased very slightly at the start of heaving at 2200 hrs.

During the event, both the surface and air temperatures remained below freezing while the soil remained much warmer (up to 6°C).

Settling commenced at 0900 hrs. when the soil surface temperature rose, but even after complete thawing did not return to its prior level entirely.

Event 2, December 11-12 (Figure 8). This event, too, is associated with precipitation: about 5 mm w.e. as snow was recorded on December 9 and 10. Higher temperatures on December 11 allowed snowmelt and frost heave followed this.

Heave started at 2000 hrs. as soon as the soil surface temperature fell to freezing point, but seems to have been interrupted by an increase in the air temperature and wind velocity at 2300 hrs. With lowering of the temperature, heave resumed at 0200 hrs. to reach a maximum of 1.3 mm at 0700 hrs. Again, the average heave rate was low (0.11 mm hr^{-1}).

Settling occurred much more rapidly as the surface temperature rose

HEAVE AND OTHER HOURLY DATA , EVENT OF 1976/11/14 TO 15

HEAVE AND OTHER HOURLY DATA , EVENT OF 1976/12/11 TO 12

and was completed by 0900 hrs.

Event 3, December 14-15 (Figure 9). The slight heave recorded during the night of December 14-15 is associated with that which occurred 48 hrs. earlier but involved warmer and drier conditions. The mean air temperature at 15 cm during the event was 4°C : much higher than that prevailing during Event 2.

Heave started as a response to a fall in temperature prior to 1900 hrs. and proceeded at a slow rate (0.18 mm hr^{-1}) to a low maximum (1.8 mm) at 0600 hrs. Subsequent settling was completed by 0900 hrs., when the surface temperature rose above 0°C .

Event 4, February 14-15 (Figure 10). This was the most significant heave event recorded during the 1976-1977 winter at Rocky Flats. It gave the greatest heave amount of the winter (6.5 mm at 0700 hrs. on February 15) and the most rapid heave rate (0.93 mm hr^{-1}). It provides the steepest heave curve recorded in three winters of work on Rocky Flats and so warrants detailed examination.

44 days of drought preceded the event but was terminated by almost 6 mm (w.e.) of precipitation as snow on February 13 and 14 (Figure 1). Immediately before the onset of heaving, air temperatures were low (-10°C at 2300 hrs.) and a 5 cm cover of snow remained on the ground at the study site. All of the heave occurred under this snow cover which seems to have retarded temperature responses at the soil surface 1.5 hrs.

Soil surface heave commenced at 0100 hrs. when the surface temperature fell to just below 0°C . Below the soil surface, temperatures remained constant throughout the event at 1°C and, at the surface, fell to only -1°C . This, too, is a response to the presence of a snow cover.

HEAVE AND OTHER HOURLY DATA , EVENT OF 1976/12/14 TO 15

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 2/14 TO 15

At 0400 hrs. air temperatures started to rise with soil surface temperatures following about 3 hrs. later. With this slight change in the surface temperature, settling commenced at 0800 hrs. and accelerated greatly at 0900 hrs. By 1100 hrs. settling was practically complete, although the soil surface remained almost 1 mm higher than it had been prior to freezing.

Two comments about this event are noteworthy. First, the presence of a 5 cm snow cover is important in attenuating temperatures. In the absence of a snow cover, heave has not been found to be associated with such cold conditions as were found during this event. Second is the fact that a significant amount of heave occurred with relatively constant, warm soil conditions: only a slight temperature gradient is needed to initiate frost heave.

Event 5, March 7-8 (Figure 11). In contrast to the preceding cases, this heave event was not a rapid response to precipitation: snowfall on March 2 was retained by cold conditions and did not become available as moisture until March 7. This is a relatively slight event (about 1 mm of heave) but it shows the usual assymetric form of heave and settling rates through time. In response to temperature fluctuations, two maxima are evident on the heave curve - a minor one at 0300 hrs. and the more usual one which is attained at 0700 hrs. Following the latter, settling is completed within 2 to 3 hrs.

Event 6, March 10-11 (Figure 12). Event 6 is the first one in a heave period which encompassed three successive nights of frost activity. It follows 3 mm of precipitation on March 10 and, like Event 4, occurred

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 3/ 7 TO 8

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 3/10 TO 11

with a thin snow cover on the ground. The latter accounts for the constancy of soil surface temperatures during the event and the low rate of ice needle ablation during the latter part of it.

Surface heave commenced at 2300 hrs. when a lowering of the soil surface temperature to -0.5°C was recorded and proceeded to a maximum of 4.1 mm at 1000 hrs. (an average rate of 0.37 mm hr^{-1}). Such a late peak on the heave curve is clearly produced by the influence of a snow cover on the thermal conditions at the soil surface.

Settling from the peak at 1000 hrs. appears to have been completed by 1600, with some residual lifting of the soil surface still evident at that time. Soon after this, heave commenced again with Event 7.

Event 7, March 11-12 (Figure 13). This event followed closely Event 6 at a time when the ground on the study site remained snow-covered with much available moisture.

Heave started at 1800 hrs. when the soil surface temperature fell to below freezing and proceeded rapidly until midnight (at an average rate of 0.62 mm hr^{-1} over this period). Following midnight, the soil surface remained at about 4 mm above its normal level until 0700 hrs. when rapid ablation of segregation ice within it followed a rise in temperature. By 1000 hrs. settling back to the level of the previous afternoon had been completed. The rapid ablation is a contrast to the previous event and suggests that by now the snow cover had been removed.

Event 8, March 12-13 (Figure 14). This is the last in a sequence of three consecutive events and, despite favorable temperature conditions, shows less heave than the two which preceded it. The limitation on heave amounts

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 3/11 TO 12

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 3/12 TO 13

during this event derives from a lack of available moisture following warm conditions on March 12.

Heave commenced at 2200 hrs. and reached a maximum (2.5 mm) at 0600 hrs. (an average heave rate of 0.36 mm hr^{-1}). Ablation and settling occurred rapidly and was practically complete by 0800 hrs.

On March 13, surface temperature at the study site rose to 33°C and this, with the evaporation it suggests, terminated the only heave period of the 1976-1977 winter.

Event 9, April 4-5 (Figure 15). This event follows a snowfall (11 mm w.e.) on April 2 which was maintained on the ground surface by low temperature during the succeeding two days (Figure 2). On April 4, snowmelt occurred with rising temperatures and the last heave event of the winter followed this release of moisture.

Heave commenced at 2300 hrs. as the surface temperature fell below freezing and continued at a rate of 0.61 mm hr^{-1} until 0600 hrs. when it reached a peak value of 4.3 mm. Settling commenced immediately after the peak on the heave curve and was completed within two hours (though a residual lifting of over 1 mm remained for at least 24 hrs.).

Summary

Low winter precipitation during 1976-1977 has reduced both the frequency of heave events and the total amounts of heave associated with each of them. Only 9 events have been recorded at Rocky Flats this winter and only one occasion were events found to occur in sequence on successive nights (in a heave period). Despite such a low frequency, the development of heave events and the circumstances under which they occur are similar

FIGURE 15

HEAVE AND OTHER HOURLY DATA , EVENT OF 1977/ 4/ 4 TO 5

to those involved in previous winters. Most heave occurs after precipitation (with a lag that varies up to 5 days). The duration of heave varies from 6 hrs. to 18 hrs. and the amount from 1 mm to 6.5 mm. Maximum heave occurs in almost all cases at 0700 hrs. (± 1 hr). The timing of the onset of both heave and ablation to the soil surface temperature and has been found to occur with a snow covered surface and in relatively windy conditions. All of these characteristics have been defined previously, from the records of the previous two winters at Rocky Flats. Apart from its low level of total activity, the 1976-1977 winter did not differ from the two preceding ones.

WIND STUDIES 1976-1977

As in previous winters, wind speed at 50 cm and 300 cm above the ground and wind direction at 300 cm were continuously recorded at the Lindsay Ranch site during 1976-1977. One reason for these observations was to allow crude estimation of the potential for soil erosion by wind action at Rocky Flats. This evaluation is based upon procedures which have been described already (Caine & Morin 1976). In essence, it rests upon the assumption of a logarithmic velocity profile (Sutton 1955; Plate 1971) and the fitting of this to only two observation points. Errors are, therefore, wide and so most emphasis is here placed upon estimates of mean conditions. These are not fully relevant to the problem of sediment entrainment into a turbulent flow but their variations through time should allow first estimates of changes in erosion potential.

Two characteristics of interest to the study of wind erosion have been estimated from the wind profile: the roughness length (Z_0) and the friction velocity (V_*). The first of these is a characteristic of the surface over which the wind is blowing (i.e. Site B at the Lindsay Ranch) and is estimated as the elevation at which the wind velocity tends to zero. V_* is an estimate of the horizontal shearing stress in the air flow and so of the stress it exerts on the underlying surface.

In this study, Z_0 and V_* have been estimated from individual gusts that are identifiable on the records of both anemometers. This allows better comparability than is attained by use of the recorder timing and a fixed interval of observation. A number (usually 25) of gust-estimates of Z_0 and V_* then provides a single day's sample from which population

x; Some data is missing for
this period (Precipitations Only).

NOTE: The vertical lines on the graph represent
daily precipitation totals.

characteristics are obtained. Most of these populations seem to approximate a log-normal distribution and so the geometric mean is used extensively for comparative purposes.

The Roughness Length

Variations in the estimated values of Z_0 for the entire period of continuous wind records at the Lindsay Ranch are shown in Figure 16. This record shows a repeated annual cycle which reflects seasonal changes in the vegetation on the site. During the summer Z_0 is relatively high (more than 5 cm) but of comparable value to that found in study over similar terrain elsewhere (Sutton 1955; Plate 1971). This is, of course, the season when the ground cover is best developed and at its greatest vertical extent. During the fall and winter, Z_0 is reduced to values of less than 2 cm. This appears to be a response to modification of the ground cover through breakage and flattening due to the wind and snow (any increase in soil roughness due to frost effects would not be sufficient to override the vegetative influence on this site). In April the cycle is brought to a close when the vegetation commences growth and, consequently, Z_0 rises back to values approaching 10 cm.

Although the variability of Z_0 merits further study, some general comments are worth making at this stage. First, the seasonal cycle defined in Figure 16 suggests that, in conditions like those found on the Lindsay Ranch site where individual patches of bare ground are of limited horizontal extent, the potential for wind erosion should be maximized during the winter months, including the periods when needle ice activity is most intense. This may not, of course, be true elsewhere on Rocky

Flats where bare ground may be more extensive and where the vegetation has a less dominant role in defining the aerodynamic character of the surface. Further, the relatively high values for Z_0 at all times of the year (except when the ground is snow-covered) suggests that frost heave occurs in a protected soil environment. This could account for the fact that we have frequently monitored needle ice growth at times of relatively high wind speed (at 3.0 m above the ground), contrary to the observations of other workers.

The Friction Velocity

Analysis of the 1975-1976 wind record from the Lindsay Ranch suggested that a critical friction velocity is exceeded quite frequently (on about 1 day in 3) (Caine & Morin 1976). In light of the lack of evident sand transport and soil erosion, V_* does not appear to be critical in defining erosion potentials: it is clearly subordinate to the surface characteristics which define Z_0 . For this reason, no further work has been completed in 1976-1977 on the nature of V_* and its variability.

It is, however, worth noting that this conclusion (that V_* is not a basic control of erosion potential) is a site-specific one. Elsewhere on Rocky Flats, or at the Lindsay Ranch site under different surface conditions, it may be insupportable.

Summary

In summary, two points emerge from this examination of wind conditions at the Lindsay Ranch study site. Both require further testing and more comprehensive analysis but, since they are corroborated by two years of records, can be stated here with more confidence than in previous reports.

First, estimated values of the roughness length suggest that little of the soil on the site is exposed to wind erosion, even under winter conditions. Second, wind shear capable of entraining soil particles into motion is common but is not effective, because of the dominance of the vegetation in controlling the aerodynamic characteristics of the surface. Any change in the surface conditions (e.g. through removal of the vegetation) would obviously require radical change in these conclusions and so could be associated with significant levels of soil erosion. Similarly, extrapolation of these results from the study site to other parts of Rocky Flats requires considerable care.

CONCLUSION

The objective of this report has been to describe and summarize field observations made as part of a study of ground freezing and surface soil erosion at Rocky Flats during the winter of 1976-1977. This period has been the final one for detailed field observation in the project: only unusual weather conditions will merit further field study in the upcoming winter.

On a broad scale, progress has been made through an empirical study of the surface soil appearance which corroborates the conclusions reached previously on the basis of soil textures alone. While further statistical analysis of the survey results is needed, it now appears clear that the interfluvial situations at Rocky Flats are the ones most prone to frost action. A high level of confidence in the mapping procedures outlined earlier (Caine & Morin 1976) is suggested by this result.

The 1976-1977 winter was one of low activity in terms of soil disturbance by frost action at Rocky Flats. Not only were relatively few surface heave events recorded (only 9 in excess of 1 mm heave in the entire winter) but the recorded events were also of low magnitude. This reflects the low amounts of precipitation during the winter and the consequently dry soil conditions. Under such dry conditions, snowfall and subsequent snowmelt is clearly important to frost heave development but, even so, the record continues to support the contention that needle ice production in a fall and spring phenomenon at Rocky Flats. This has been supported during the entire period of our study.

With relatively few needle ice events, the variety of environmental

conditions associated with them has not been as great in 1976-1977 as in previous winters. In general, however, the pattern and control of frost heave have been identical to those found in previous winters. We have also continued to find that surface heave occurs under a thin snow cover, at times when air temperatures are above freezing and with relatively high wind speeds. Needle ice growth under all three of these conditions has been reported as rare in other work.

Analysis of the wind records from the Lindsay Ranch site has also confirmed the tentative conclusions reached earlier (Caine & Morin 1976). It suggests that the vegetation controls the aerodynamic nature of the study site and that there may be little potential for wind erosion as long as the present ground cover is maintained. However, removal of the vegetation would expose soil material to wind conditions that are capable of producing erosion very frequently.

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GRAPH OF DAILY MAX. AND MIN. VALUES FOR SELECTED DATA... 1976-77 WINTER... 1976/10/ 8 TO 1977/ 4/25 THE VERTICAL DOTTED LINES ON THE GRAPH REPRESENT THE 9 SELECTED HEAVE EVENTS

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GRAPH OF DAILY MAX. AND MIN. VALUES FOR SELECTED DATA... 1976-77 WINTER... 1976/10/ 8 TO 1977/ 4/25 THE VERTICAL DOTTED LINES ON THE GRAPH REPRESENT THE 9 SELECTED HEAVE EVENTS