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

Second Progress Report

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October 1, 1975 - May 30, 1976

Prepared for the U.S. Energy Research and Development
Administration under Contract E(11-1) - 2517

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ABSTRACT

This report summarizes information on soil frost effects collected on Rocky Flats during the 1975 - 1976 winter. The work has been pursued at two scale levels.

On a broad scale, work on soil textures at and just below the ground surface corroborates the conclusion reached earlier that the general frost susceptibility of the Rocky Flats soils is quite well keyed to topography. This is incorporated into a mapping procedure for potential soil frost activity which is applied to the northwestern part of the Rocky Flats area.

On a site scale, instrumental records of weather conditions and soil responses have been maintained from October, 1975, to May, 1976, at the Lindsay Ranch study site, northwest of the Rocky Flats Plant. During that period, 33 needle ice events have been observed and recorded and are described in this report. A preliminary examination of wind data for the same period suggests that the soil in areas of 'natural' vegetation on the site are not exposed to wind action. If, however, they were exposed, winds capable of eroding them are common.

INTRODUCTION

This is the second progress report of research into needle-ice growth, soil surface changes, and wind erosion at Rocky Flats, Colorado. It reports results from the first complete winter in which records have been maintained on the study site at the Lindsay Ranch. As yet, the analysis of these records and their application to evaluating the nature of frost action is incomplete and so this report is largely descriptive in nature. It will be supplemented by a later progress report (to be completed before October 1, 1976) of a more analytical nature.

The Problem

In general, the study is concerned with evaluating the possible interactions between frost action in the soils of the Rocky Flats area and later removal of surface soil by wind erosion. Such interaction may be at the base of plutonium resuspension from a contaminated soil and could be significant wherever contaminated soil is present in an environment where frost occurs. The interaction of frost and wind erosion was initially suggested by the coincidence of seasonal fluctuations in airborne Pu. concentrations with periods of potential frost action (Caine and Morin, 1975).

For the current period of support, four objectives were outlined in the work proposal and can be usefully summarized here:

1. Mapping of the Rocky Flats area at a scale of 1:12,000 for soil frost susceptibility and wind erosion potential.

2. The documentation of weather and soil conditions during the 1975 - 1976 winter at the Lindsay Ranch site, particularly during the times when diurnal freezing and thawing of the soil surface is going on.
3. A preliminary evaluation of wind effects in conjunction with the record of soil frost events at the Lindsay Ranch.
4. The fitting of a simulation routine for needle ice development to the record from the Lindsay Ranch site.

Progress toward these four objectives has been uneven in the past nine months and work on all of them continues at the present time.

Previous Work

Earlier work on this project was reported in the first progress report which summarized observation made during the latter part of the 1974 - 1975 winter. This initial period of work was of a reconnaissance nature and served to show that needle ice events occurred on Rocky Flats and to test procedures and instrumentation for field use. Six episodes of soil freezing and thawing were recorded in 1974 - 1975 but instrumental records of meteorologic conditions during these events are uneven and incomplete. Records of wind conditions for the 1974 - 1975 winter on the Lindsay Ranch site are perhaps the most significant gap in our knowledge of that winter.

Calendar

Some background weather observations were maintained on the Lindsay Ranch site during the 1975 summer but detailed records were not started until October 2nd. At this time, conditions become such that soil freezing is

possible at the elevation of Rocky Flats. The program of observation was terminated for the summer on April 15, 1976, at which time soil frost was extremely unlikely. A summary of instrumentation and observation is listed in Table 1.

Personnel

The following personnel have worked on this project in the period October 1975 - June 1976:

Nel Caine-	Principal Investigator, 15% time.
Carol Jenner-	Co-Principal Investigator, 2 1/2 months.
John Clark-	Instrumentation Technician, 1/2 month.
Rolf Kihl-	Laboratory Technician, 1 month.
Pierre Morin-	Graduate Research Assistant, 50% time.
Cliff Mitchell-	Undergraduate Assistant, 25% time.
Jan Cassin-	Undergraduate Assistant, 25% time.
Margaret Eccles -	Data Analyst, 1 1/2 month.

In addition, Dr. S. I. Outcalt, University of Michigan, has made three visits to Boulder in connection with the project.

During the next three months, Morin will be employed full time for two months and Caine for one month, Jenner for one month in data analysis and preparation of a third progress report. Further work in the field by Morin and Mitchell will be necessary in the same period of time to complete mapping of soil frost susceptibility.

This Report

The body of this report has a pattern similar to that of the first

TABLE # 1

1975 - 1976: Continuous Recordings

<u>DATA</u>		<u>DATES</u>		<u>PRECISION</u>
Air temperature	2 m	4.15	to present	± 1 degree C
Air humidity	2 m	4.15	to present	$\pm 3\%$
Precipitations		4.15	to present	± 1 mm
Soil temperatures				
Depth	0 cm	10.3	to present	± 0.25 degrees C
	2 cm	10.1	to present	"
	5 cm	10.8	to 3.17	"
	10 cm	3.22	to present	"
Air temperature	15 cm	10.2	to present	"
Soil Heave		10.2	to present	± 0.25 mm
Net radiation		4.7	to present	± 0.05 ly/mm
Wind speed	3m	9.8	to present	± 1 mph
Wind speed	0.5m	9.8	to present	± 1 mph
Wind direction	3m	9.8	to present	± 15 degrees

1975 - 1976: Discontinuous Recordings

From January 20, 1976, to present:

- Soil moisture and soil temperature at 5, 10, and 20 cm deep at sites Ba, D2a, and Ea.
- Soil temperature at 2, 5, 10, and 20 cm deep (at site Bb) and at 10 and 20 cm deep (at site D2b and Eb).

INSTRUMENTATION AND CALENDAR OF OBSERVATIONS

progress report (Caine and Morin, 1975). The two main parts of the report concern (1) studies in progress on a fairly wide scale; and (2) site studies and records from the Lindsay Ranch study site. Most of the winter field effort was put into the second of these and for that reason it makes a large part of this report.

BROAD-SCALE STUDIES

Two sub-programs are originally included under this heading: those involving a larger spatial scale than that of the detailed study site at the Lindsay Ranch. No further work on the first of these has been done in the past year and so reference should be made to Caine and Morin (1975) for an examination of the potential for frost action and wind erosion estimated from a six year weather record from Rocky Flats. The second of these sub-programs requires the estimation of the susceptibility of the surface soil on the Rocky Flats area to frost action and erosion. Progress toward the production of a map of these soil characteristics for the area is described here. A map of soil frost susceptibility should be completed in draft form before the end of the 1976 summer.

It has been known for decades that the texture of soils exerts a control on their frost susceptibility which is independent of temporal fluctuations in the frequency and intensity of freezing temperatures and in their moisture status (e.g. Taber, 1930; Beskow, 1935). Similarly, estimates of soil texture are required in many empirical routines for indexing the erodibility of soil material, either by water or by the wind (Chepil and Woodruff, 1963; Farmer, 1973). For these reasons, emphasis has been placed

upon the study of spatial patterns in soil surface textures on Rocky Flats. This is not entirely satisfactory since it takes no account of other influences on frost action or wind erosion, and since the textural estimators of frost susceptibility and erodibility are not entirely compatible: the influence of soil aggregates on erodibility is especially important.

Sampling

On Rocky Flats, soil sampling for textural analysis has been conducted at two levels in the profile: 0 - 2 cm. and 10 - 15 cm. depth. The rationale for this procedure is that the uppermost of these levels should be characteristic of the soil disturbed by needle ice growth, and subject to wind erosion, while the material from lower depths should be approximately representative of the soil from which water is drawn for segregation ice development. The requirements of analysis for the two depths are, therefore, rather different.

Spatially, sampling has been stratified by topographic position, since preliminary work on the Lindsay Ranch site (reviewed in first progress report) showed topography and near-surface soil textures to be related. Three topographic situations are identified: (1) the interfluvial situations of the Rocky Flats surface; (2) valley-side situations, on the walls of the valleys cut into the Rocky Flats surface, and (3) the valley floors. Field observations of needle ice on Rocky Flats support the contention that this stratification is meaningful for the study of frost action.

Soil Textures

The results of sampling for soil textures on the northwestern part of

the Rocky Flats area are summarized in Figures 1,2,3, and 4. For the most part, the less than 2 mm. calibre material is a sandy loam, with some important differences. There is a clear difference in the proportions of clays with depth in soil profile (Table 2), which may be interpreted as a response to normal pedogenic eluviation of clays from the surface levels or as reflecting removal of fines from the soil surface by wind erosion. In view of the fact that the difference is greatest on the exposed interfluvial areas, where the soil is also armored by a lag gravel, the latter explanation is favored. At equivalent depths below the ground surface, there are no major textural differences between the fine fractions of soils on the interfluvies and those on the valley sides. When the coarser - than - 2 mm. fraction is included in the analysis, however, a slight difference between the two appears, particularly in the proportion of fragments larger than 2 mm. size (Figures 3 and 4). Since the valley-side sediments are presumed to have been derived from those on the interfluvies, following transportation by mass wasting, this is not surprising. A further difference between interfluvial and valley-side soils is also evident in the difference in the proportions of clay-size material (under 4 μ) at the surface and at 10 cm. below the surface (Table 2).

The main spatial difference in soil textures occurs between the interfluvial and valley-side materials and those of the valley floors (Figure 1, 2,3, and 4). This is evident however the data is presented. On the valley floors, there seem to be two types of sediment, both clearly different from the interfluvial and valley-side materials. One type consists of very sandy material and has been found in the narrow valley northwest of the Lindsay Ranch and close to creek beds elsewhere. This is interpreted as transported

Table 2

SURFACE / SUB-SURFACE DIFFERENCE IN CLAY CONTENTS

Situation	N	$\bar{x}$	$\hat{\sigma}^2$	$\hat{\sigma}$
Interfluve	10	9.5%**	18.7	4.32%
Valley-side	10	4.6 **	13.7	3.7
Valley-floor	10	0.4	14.0	3.8

Analysis of Variance

Source	S.S.	d.f.	M.S.	F
Between Sitns.	410.3	2	205.2	13.24**
Within Sitns.	418.2	27	15.5	
TOTAL	828.5	29		

Least Significant Difference ($p = 0.05$): 4.06%.

Probability Levels: ** : $p < 0.01$.

(Significance levels on the means ($\bar{x}$) are based on a paired t test of $H_0: x = 0.0$).

Figure 1 TEXTURE TRIANGLE: PARTICLES SMALLER THAN 2 mm (Depth, 0-2 cm)

Figure 2 TEXTURE TRIANGLE: PARTICLES SMALLER THAN 2 mm (Depth, 10-15 cm)

Figure 3 TEXTURE TRIANGLE: BULK SAMPLE (Depth, 0-2 cm)

Figure 4 TEXTURE TRIANGLE:
BULK SAMPLE (Depth, 10-15 cm)

sediment, probably moved by fluvial action. The second type is of much finer material in the broader valleys of Rocky Flats and is assumed to have developed in situ from the underlying Pierre Shale. A preliminary textural analysis (first progress report) also suggested the differentiation of the valley floor materials in this manner.

Frost Susceptibility

Although the texture triangles for surface soil include the frost susceptibility criterion of Beskow (1935), this is not particularly useful in defining levels of susceptibility. Practically all the surface materials sampled on Rocky Flats fall within the envelope of susceptibility which then loses any usefulness in distinguishing materials. The definition of quantitative dimensions of frost susceptibility requires more work but initially it is approached here through the use of the percent sand in the surface soil. This is only possible because the Rocky Flats samples arrange themselves approximately along the bisector of the susceptibility envelope, so allowing the reduction of two dimensions to one. The dependence of needle ice development on the sand fraction of surface soil has not yet been defined. Qualitatively, we suggest that it should have a form like that shown in Figure 5, as a product of the variations in hydraulic conductivity and soil suction with particle size.

In considering the percent sand in the less - than - 2 mm. fraction of the surface soil, three situations on Rocky Flats are shown to be statistically different (Table 3). These are (1) the interfluvial and valley-side areas, where the soil is derived from the Rocky Flats alluvium; (2) the areas of sandy valley floor, of transported and sorted Rocky Flats alluvium, and (3) the valley floor materials derived from the Pierre Shale.

Table 3

SURFACE SOILS: SAND CONTENT

Situation	N	$\bar{x}$	$\hat{\sigma}^2$	$\hat{\sigma}$
Interfluv	12	57.7%	19.9	4.5%
Valley-side	13	59.2	43.7	6.6
Valley-floor (s)	7	72.7	62.3	7.9
Valley-floor (f)	4	32.6	36.3	6.0

Analysis of Variance

Source	S.S.	d.f.	M.S.	F
Between Sitns.	4120.1	3	1373.4	
				35.9 **
Within Sitns.	1225.5	32	38.3	
TOTAL	5345.6	35		

Least Significant Difference ($p = 0.05$): 3.16%.

Significance levels: ** : $p < 0.01$.

All estimates are based on the finer-than-2 mm. fraction only.

In the valley-floor situations: (s) refers to sandy sediments,

(f) refers to finer sediments.

This classification, in combination with Figure 5, suggests that the most susceptible materials to needle ice segregation are those on the interfluves and valley sides.

Water Relationships

The 10 - 15 cm. depth in the soil is used here as an estimator of the moisture reservoir from which water for ice segregation is drawn. For present purposes, 'available water' is used as an index of the volume of water potentially available below the surface for needle ice growth. This is defined as the difference in gravimetric water content between field capacity and wilting point, i.e. at soil suctions equal to -0.3 bars and -15 bars respectively. Segregation could draw upon moisture held at higher tensions than -15 bars, but, since the moisture retention curves for the Rocky Flats soils are log-linear and almost parallel (first progress report, page 16), the use of available water as an index (not an absolute measure) is reasonable. A simple relationship between available water and soil texture is clearly evident in Rocky Flats materials (Figure 6).

Analysis of variance of the available water estimates for the 10 - 15 cm. depth sediments shows a significant ($p = 0.05$) difference between all three topographic situations included in the analysis (Table 4). The differences between interfluves, valley-sides, and sandy valley-floors seems to be a real one. (The valley-floor sediments of finer material were not included in the analysis because of their very low variance estimate.) The difference defined by Table 4 is substantiated by that suggested by a smaller data set and different characteristics in the first progress report (page 12.).

Figure 5 FROST SUSCEPTIBILITY AND SAND CONTENT

Figure 6 RELATION BETWEEN AVAILABLE WATER AND SAND CONTENT

Table 4

SUB-SURFACE SOILS: AVAILABLE WATER

<u>Situation</u>	<u>N</u>	<u>$\bar{x}$</u>	<u>$\hat{\sigma}^2$</u>	<u>$\hat{\sigma}$</u>
Interfluve	10	9.1%	2.8	1.7%
Valley-side	10	6.4	4.0	2.0
Valley-floor (s)	7	5.2	2.5	1.6
Valley-floor (f)	4	13.2	0.2	0.5

Analysis of Variance

<u>Source</u>	<u>S.S.</u>	<u>d.f.</u>	<u>M.S.</u>	<u>F</u>
Between Sitns.	69.06	2	34.52	
				10.88 **
Within Sitns.	76.14	24	3.17	
TOTAL	145.2	26		

Least Significant Difference ($p = 0.05$): 1.06%.

Significance Levels: ** : $p < 0.01$.

All estimates are based on the finer-than-2 mm. fraction only.

In the valley-floor situation: (s) refers to sandy sediments;

(f) refers to finer sediments.

Available water is defined as the difference in water contents at 15 bar and 0.3 bar suction.

Valley-floor (f) samples excluded from Analysis of Variance because of inhomogeneity in the sample variances.

Mapping Potential Frost Effects

This work on soil textures was undertaken to give a basis for mapping the potential of the Rocky Flats surface soils for ice segregation. It has served to define environmental differences in two sets of controls of frost action which are now being used in mapping spatial patterns. The first set differentiates the susceptibility of the surface material to ice segregation and suggests a three-way classification: (1) Interfluves and Valley-sides; (2) Valley Floors (fine sediments), and (3) Valley Floors (sandy sediments). This sequence runs from higher to lower susceptibility. The second set involves the potential storage of moisture close to the soil surface and suggests a four-way classification: (1) Valley-floors (fine sediment); (2) Interfluves; (3) Valley-sides, and (4) Valley-floors (sandy sediment).

The combination of these two classifications gives the four classes of 'soil frost potential' which are in use in mapping on Rocky Flats. From greatest to least potential, these are:

- 1) Interfluve situations
- 2) Valley-sides of Rocky Flats alluvium
- 3) Valley-floors (fine sediment) in Pierre Shale
- 4) Valley-floors (sandy, transported sediment)

Further validation of these classes is needed, and the survey information which might allow quantitative estimates of frost potential to be applied to this scale. The application of these classes to a part of the Rocky Flats area is exemplified in Figure 7 (which combines classes 3 and 4).

Figure 7 PRELIMINARY MAP OF THE SOIL FROST SUSCEPTIBILITY (ZONE A.N.W.)

Note : The map is based only on granulometric and hydrologic characteristics of 30 soil samples.

SITE STUDIES

General Conditions

Between November 1, 1975, and April 15, 1976, 26 heave events were recorded instrumentally and on 7 additional days needle ice formation was observed in the field. This section of the report is concerned with the detailed observation of 11 selected heave events and with the description of the corresponding conditions. A more complete study of the heave record will appear in the supplementary report. Table 5 is a calendar summarizing the soil frost observations; it shows that the 33 individual events can be grouped into 8 periods of heave activity, the longest of which lasted from March 7 to March 16, 1976. The distribution of the heave events confirms that the period at the beginning and at the end of the winter are the most active ones. March and November account for 22 of the 33 cases.

A similar pattern of meteorologic conditions is associated with many of the heave/needle ice events. This pattern starts with a cool, moist air mass over the Colorado Piedmont which gives precipitation, often as snow. Figure 9 shows the precipitation record for the days preceding needle ice events in 1975 - 1976: up to 18.4 mm. of water equivalent have been observed immediately before surface heave. Melting of the snow with relatively low temperatures but high radiative exchanges then starts a sequence of diurnal heaves. The maximum amount of heave is often recorded 1 to 2 days after the cessation of precipitation (presumably reflecting the time needed to melt the snow cover). The entire sequence is eventually terminated by either the advection of warmer air to prevent temperatures falling below 0 Degrees C or by the desiccation of the soil near the surface through evaporation or sublimation.

TABLE 5 HEAVE EVENTS, WINTER 1975 - 1976

<u>Night Preceding Event</u>		<u>Recorded Event</u>	<u>Observed Event</u>
November	10-11	*** ▶	
	11-12	*** ▶	***
	12-13	*** ▶	***
	13-14	*** ▶	
	14-15	***	
	15-16	***	
	23-24	***	***
	25-26	***	
	26-27	***	
	27-28	***	
	28-29	***	
December	19-20	***	
	20-21	***	***
	21-22	***	***
	22-23	***	***
January	20-21	***	
	21-22	*** ▶	
	22-23	*** ▶	
	28-29		***
February	22-23		***
	24-25		***
	26-27		***
March	6-7	***	
	7-8	***	***
	8-9	*** ▶	
	9-10		***
	10-11		***
	11-12	*** ▶	
	12-13	*** ▶	
	14-15		***
	15-16	***	
	29-30	*** ▶	
	30-31	*** ▶	***

*** Recorded heave event: instrumentally recorded and measured heave.

*** Observed heave event: field observation of well developed needle ice.

▶ Heave events selected for this report.

Figure 8 SOIL SURFACE HEAVE RECORD AT SITE B DURING THE 1975 - 1976 WINTER .

NOTE: All heave values are recorded to the tenth of mm.

Figure 9 RECORDED PRECIPITATION DURING EACH WAVE EVENT PERIOD (1/10s of an)

11 sets of frost heave observations were selected for inclusion in this report as representative of the different parts of the 1975 - 1976 winter. The periods described here are the ones which will be used in simulating the environment of needle ice growth at Rocky Flats.

Heave Records

For the 11 selected events, instrumental records are only available from Plot B, on the interfluvium at the Lindsay Ranch site. Table 6 and Figure 8 (a,b) summarize the hourly values of soil surface heave. The average amount of surface movement is 5.2 mm. (cf. 5.5 mm. in 1974 - 1975) with a maximum of 10.5 mm. at 0700 on November 11. The longest duration for a heave cycle was 22 hours (November 11) and the shortest cycle lasted 6 hours, on November 14. There is no obvious relationship between the duration and amplitude of heave but there is a tendency for longer events to give greater surface lifting. The maximum values of heave were recorded at 0700 $\pm$ 1 hour with the sole exception of January 23 (0200). The general shape of the uplift curve shows a slow rate of lifting (followed in some cases by a stable heave ceiling) and a more rapid return to the normal ground surface. These observations conform to the temporal pattern of needle ice growth described in the literature (e.g. Outcalt, 1970, 1971; Fahey, 1973; Caine and Morin, 1975).

The last heave event of the winter occurred on March 31. This is 15 days earlier than its equivalent in 1974 - 1975, the earlier cessation being associated with a dry April in 1976. A dry spring also suggests that the number of days on which frost heave or needle ice was recorded in 1975 - 1976 (33 days) was probably less than average for Rocky Flats. The discrepancy between the numbers of observed and recorded events suggests that

RECORDED HEAVE EVENTS FOR 1975 - 1976

All Values of Heave in 10th of mm. Table # 6

MEAN VALUES	.91	4.3	7.1	10	12	16	26	23	27	30	35	41	43	46	49	50	39	27	13	5	4	3		
Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
November 10 and 11, 1975										0	12	24	35	45	54	65	76*	65	47	13	10			
November 11 and 12, 1975	10	13	35	48	58	65	72	79	85	89	92	97	99	101	103	105*	103	91	55	35	31	29		
November 12 and 13, 1975		28	33	39	42	50	58	65	70	75	79	85	86	86	87*	80	52	28						
November 13 and 14, 1975												27	28	32	37	38*	25							
January 21 and 22, 1976						7	8	9	12	15	21	24	26	28	28	28*	28	25	10	4	1	0		
January 22 and 23, 1976				0	2	5	11	16	23	25	31*	30	25	24	25	27	27	20	8	5				
March 6 and 9, 1976				3	6	11	17	25	28	36	41	43	46	50	51	52*	27	11	3	0				
March 11 and 12, 1976						0	3	7	13	14	14	14	12	12	15	16*	15	10	6					
March 12 and 13, 1976		6	10	20	29	33	38	41	45	46	48	49	50	50	51*	50	48	34	15	0				
March 29 and 30, 1976										0	3	7	11	16	19	20*	10	7	2					
March 30 and 31, 1976							2	4	10	19	29	40	49	57	65	70*	57	20	10					

*Maximum Value

the heave recorder at Plot B is not well sited to record all cases of frost heave. We propose to increase the number of heave sensors in the future to allow a clearer evaluation of this.

Visual estimates of the amount of the ground surface disturbed by needle ice have been made whenever observers were in the field in 1975 - 1976. During the winter, between 30% and 40% of the interfluvial surface was affected to some degree and ice needles up to 25 mm. long were measured at Plot D (i.e. more than twice the maximum recorded instrumentally at Plot B).

During the 11 sets of heave observations summarized here, the following parameters have been recorded and used in this summary: air temperature and relative humidity measured in a standard instrument screen; air temperature at 15 cm. above ground, measured by YSI thermistor under a radiation shield; soil/air interface temperature (probably responding to radiation also), soil temperatures (YSI thermistors) at -2 and -5 cm. and wind speeds measured at 0.5 and 3 m. above ground. Hourly or bi-hourly summaries are shown in Tables 7 to 14. Figures 10 to 20 present a graphic illustration of the same records while the following section of the report is a description of each event.

Heave Events

a) Event 1, November 10 and 11, Figure 10.

Heave Curve: Heaving of the soil surface started at 0100 hours on November 11, and lasted for 11 hours. Maximum heave (7.6 mm.) was recorded 7 hours after the onset.

RECORDED AIR TEMPERATURES IN SCREEN 1975 - 1976

All Values Are in Degrees Centigrades

Hours of Day	16	18	20	22	24	2	4	6	8	10	12	14
November 10 and 11, 1975	3	3	4	3	1	-1	-2	-2	-2	-1	3	3
November 11 and 12, 1975	-3	-3	-4	-4	-4	-5	-5	-4	-2	1	1	2
November 12 and 13, 1975	0	-3	-3	-2	0	3	4	6	10	16	12	13
November 13 and 14, 1975	11	8	7	4	7	6	7	8	9	13	16	18
November 14, 1975	16	12	11	10	9							
January 21 and 22, 1976		4	3	5	4	2	3	5	5	10	12	12
January 22 and 23, 1976	11	7	7	7	7	6	7	6	5	8	10	11
January 23, 1976	8	6	5	4	4							
March 8, 1976										0	1	
March 8 and 9, 1976	1	-1	-5	-4	-4	-6	-5	-3	3	6	7	7
March 9, 1976	4	2	1	2	1							
March 11, 1976						1	0	1	4	1	1	4
March 11 and 12, 1976	3	0	-10	-12	-14	-15	-16	-16	-14	-11	-11	-10
March 12 and 13, 1976	-11	-12	-13	-14	-9	-8	-5	-2	-1	4	5	5

TABLE 7

RECORDED AIR TEMPERATURES IN SCREEN 1975 - 1976 Continued

All Values Are in Degrees Centigrades

Hours of Day	16	18	20	22	24	2	4	6	8	10	12	14
Marcy 13, 1976	4	2	1	0	0							
March 29 and 30, 1976			-7	-10	-11	-12	-10	-7	-4	-3	-2	-1
March 30 and 31, 1976	-1	-2	-5	-7	-9	-7	-8	-4	0	4	6	6
March 31, 1976	3	1	0	0	2							

TABLE 7, cont.

RECORDED HOURLY AIR TEMPERATURES AT +15CM FOR 1975 - 1976

All Values Are In Degrees Centigrades

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nov. 10 & 11, 1975											7	6	5	4	4	3	3	4	4	5	5	5	4	4
Nov. 11 & 12, 1975	4	3	2	2	2	1	2	2	1	1	1	1	1	1	1	2	2	4	7	8	8	9	8	9
Nov. 12 & 13, 1975	8	5	2	2	1	0	3	3	3	5	3	6	7	8	7	10	13	16	19	22	23	19	18	18
Nov 13 & 14, 1975	18	14	10	9	8	8	9	7	7	8	8	8	7	7	7	12	12	15	18	19	22	22	23	24
Nov. 14, 1975	22	19	16	15	13	12	13	14	16	13														
Jan 21 & 22, 1976				7	5	5	5	4	7	7	7	4	5	6	8	9	11	13	14	15	16	18	17	18
Jan 22 & 23, 1976	17	16	13	12	10	14	11	11	6	13	9	11	12	13	12	12	9	12	14	15	16	17	17	17
Jan. 23, 1976	15	13	12	11	11	10	10	10	10	10														
March 8, 1976																					11	12	11	
Mar. 8 & 9, 1976	11	11	10	7	5	4	3	3	4	2	2	2	3	1	2	3	8	11	13	15	16	17	18	18
March 9, 1976	17	15	12	12	11	11	11	12	11	11														
March 12, 1976											-4	-5	-5	-6	-7	-6	-5	-4	-3	-2	0	0	0	0
Mar. 12 & 13, 1976	0	0	-1	-3	-3	-4	-4	-4	-6	-5	-3	-3	-2	1	5	6	7	9	9	14	15	15	16	13
March 13, 1976	15	14	12	11	11	11	10	9	9	9														
Mar 29 & 30, 1976						4	4	2	1	-2	-3	-3	-3	-3	-2	-1	3	5	6	6	7	7	7	8
Mar 30 & 31, 1976	8	9	8	7	6	6	4	3	0	-1	0	-1	-1	-1	-2	0	4	7	9	13	15	16	18	18
March 31, 1976	18	17	15	12	9	9	8	8	6	8														

TABLE 8

RECORDED HOURLY SOIL-AIR INTERFACE TEMPERATURES 1975 - 1976

All Values Are In Degrees Centigrades

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nov. 10, 1975																						4	4	3
Nov. 10 & 11, 1975	3	3	3	3	3	3	3	3	2	2	0	0	0	0	0	0	-1	0	0	3	5	5	3	3
Nov. 11 & 12, 1975	2	0	-1	+1	-1	-1	-1	-1	-1	-1	-2	-2	-2	-2	-3	-2	-2	-1	1	3	4	9	10	8
Nov. 12 & 13, 1975	4	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-2	-2	-2	-1	-2	0	0	2	12	15	17	15	14
Nov. 13 & 14, 1975	10	5	2	1	0	0	0	0	0	0	0	-1	-1	-1	-2	-2	-1	1	9	15	19	20	18	16
Nov. 14, 1975	11	7	5	4	2	1	2	2	3	3														
Jan. 21 & 22, 1976				-0	-0	-1	-1	-1	-1	-2	-2	-3	-3	-3	-4	-3	-3	-2	0	1	3	6	8	7
Jan. 22 & 23, 1976	5	3	0	-2	-0	-1	-1	-1	-1	-2	-2	-2	-1	-1	-1	-2	-2	-2	1	2	5	8	9	9
Jan. 23, 1976	6	3	2	2	1	1	1	1	1	0														
March 8, 1976																						0	0	0
March 8 & 9, 1976	0	1	1	0	0	-1	-1	-1	-1	-1	-2	-2	-2	-2	-2	-2	-1	0	5	6	11	15	22	26
March 9, 1976	20	14	5	3	2	3	3	2	2	2														
March 11, 1976											-1	-1	1	2	1	1	2	8	11	15	15	4	6	35
Mar. 11 & 12, 1976	35	35	20	2	3	1	-1	-2	-3	-3	-2	-2	-3	-3	-3	-2	-2	0	0	1	4	10	8	10
Mar. 12 & 13, 1976	6	4	-2	-5	-7	-7	-7	-8	-9	-9	-10	-9	-9	-9	-8	-3	-1	1	3	12	19	18	15	10
March 13, 1976	21	19	7	3	3	3	2	2	2	1														
March 29 & 30, 1976						1	1	0	0	-1	-1	-2	-2	-2	-2	-2	-1	0	1	3	4	4	8	11
Mar. 30 & 31, 1976	9	9	6	4	0	-1	-1	-1	-1	-2	-2	-2	-2	-2	-3	-2	-1	0	4	15	23	29	31	32
March 31, 1976	28	21	12	5	3	2	1	1	0	0														

TABLE 9

RECORDED HOURLY SOIL TEMPERATURES AT 2CM DEEP 1975 - 1976

All Values are in Degrees Centigrades

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nov. 10, 1975																						4	4	4
Nov. 10 & 11, 1975	4	4	4	4	4	4	4	4	4	3	3	2	2	2	2	2	2	1	1	2	2	3	3	3
Nov. 11 & 12, 1975	2	2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	2
Nov. 12 & 13, 1975	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	5	7	7	6
Nov. 13 & 14, 1975	6	6	5	5	4	4	3	3	3	3	3	3	3	3	2	2	2	2	4	6	7	9	9	8
Nov. 14, 1975	8	7	7	6	6	5	5	5	5	5														
Jan. 21 & 22, 1976					1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	2	3
Jan. 22 & 23, 1976	3	3	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	2	4	5	5
Jan. 23, 1976	4	4	4	3	3	3	3	2	2	2														
March 8, 1976																						1	1	2
Mar. 8 & 9, 1976	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	4	7	8	8
March 9, 1976	7	7	6	5	4	4	4	4	3	3														
March 11, 1976											4	4	4	4	4	3	3	4	6	8	7	6	5	7
Mar. 11 & 12, 1976	8	7	7	6	6	5	4	3	3	3	3	3	2	2	2	2	2	2	2	2	3	5	5	5
Mar. 12 & 13, 1976	4	4	3	3	2	2	2	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	4	5
March 13, 1976	5	5	5	4	4	3	3	3	3	3														
Mar. 29 & 30, 1976					4	4	3	3	3	3	3	3	2	2	2	2	2	2	2	2	4	5	7	7
Mar. 30 & 31, 1976	8	8	7	6	5	4	4	4	3	3	3	2	2	2	2	2	2	2	2	5	9	11	13	14
March 31, 1976	13	12	11	10	8	8	7	6	6	5														

TABLE 10

RECORDED HOURLY SOIL TEMPERATURES AT 5CM DEEP 1975 - 1976

All Values Are In Degrees Centigrades

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14			
Nov. 10, 1975																						10	10	9			
Nov. 10 & 11, 1975	9	9	9	9	9	9	9	9	9	9	8	8	8	8	7	7	7	7	7	8	8	9	8	8			
Nov. 11 & 12, 1975	8	8	7	7	7	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6	7	8	8			
Nov. 12 & 13, 1975	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	9	11	11	12			
Nov. 13 & 14, 1975	12	11	11	10	10	9	9	9	8	8	8	8	8	8	8	8	7	7	8	NA-----							
Nov. 14, 1975	NA-----																										
Jan. 21 & 22, 1976				7	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	7	8			
Jan. 22 & 23, 1976	8	8	8	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6	6	7	8	9	10			
Jan. 23, 1976	10	10	9	9	8	8	8	8	8	8																	
March 8, 1976																						6	6	6			
Mar. 8 & 9, 1976	7	7	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	7	9	11	12			
March 9, 1976	12	11	11	10	9	9	9	8	8	8																	
March 11, 1976											9	9	8	8	8	8	8	8	9	11	11	10	10	10			
Mar. 11 & 12, 1976	12	12	12	12	11	10	9	9	8	8	8	7	7	7	7	7	7	7	7	7	7	8	9	9			
Mar. 12 & 13, 1976	9	9	8	8	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	7	9			
March 13, 1976	10	10	10	9	9	9	9	8	8	8																	
Mar. 29 & 30, 1976							(the values for March 29 to 31 are from 10 cm deep)																				
							9	8	8	8	8	8	8	8	7	7	7	7	7	7	7	8	8	9			
Mar. 30 & 31, 1976	10	10	10	10	10	9	9	8	8	8	8	8	8	7	7	7	7	7	7	7	8	10	11	12			
March 31, 1976	13	13	13	13	13	12	12	11	11	10																	

TABLE 11

RECORDED AIR RELATIVE HUMIDITY IN SCREEN 1975 - 1976

All Values Are In Percent

Hours of Day	16	18	20	22	24	2	4	6	8	10	12	14
Nov. 10, 1975											50	68
Nov. 10 & 11, 1975	62	55	64	60	43	45	40	35	25	30	35	34
Nov. 11 & 12, 1975	34	36	36	40	38	37	34	30	34	34	35	35
Nov. 12 & 13, 1975	41	38	50	40	36	30	25	24	20	14	26	26
Nov. 13 & 14, 1975	26	32	35	36	28	29	23	16	20	22	20	17
Nov. 14, 1975	10	14	14	15	17							
Jan. 21 & 22, 1976		30	35	26	28	30	24	24	22	19	15	14
Jan. 22 & 23, 1976	12	13	12	13	12	13	14	14	14	14	14	12
Jan. 23, 1976	14	20	28	30	30							
March 8, 1976											40	41
Mar. 8 & 9, 1976	62	84	70	62	50	64	50	50	34	26	25	24
March 9, 1976	25	30	34	32	33							
March 11, 1976						64	49	45	41	33	37	37
Mar. 11 & 12, 1976	32	36	100	100	100	100	100	100	90	82	68	62
Mar. 12 & 13, 1976	70	90	99	100	58	40	24	18	20	17	17	18
March 13, 1976	19	20	22	23	24							
Mar. 29 & 30, 1976			79	87	88	80	62	50	44	40	40	40
Mar. 30 & 31, 1976	43	48	62	72	100	80	96	74	60	44	41	40
March 31, 1976	54	60	70	-55	41							

TABLE 12

RECORDED WIND SPEEDS AT 0.5M ABOVE GROUND 1975 - 1976

All Values Are In Miles Per Hour

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nov. 10, 1975																								
Nov. 10 & 11, 1975	4	8	8	6	8	6	4	20	26	32	42	44	26	34	24	28	30	37	32	16	25	34	25	23
Nov. 11 & 12, 1975	20	23	24	21	12	12	22	22	29	29	34	37	29	29	29	18	16	15	17	7	6	6	6	4
Nov. 12 & 13, 1975	6	6	5	4	2	2	2	2	3	3	3	4	5	5	4	8	14	6	8	10	10	9	10	3
Nov. 13 & 14, 1975	0	0	6	1	4	3	4	5	3	3	7	5	4	4	5	4	6	5	4	5	6	4	3	3
November 14, 1975	14	13	13	10	4	3	4	5	4	3														
Jan. 21 & 22, 1976				4	6	5	6	4	4	5	5	3	6	5	8	6	6	8	26	25	18	25	24	22
Mar. 22 & 23, 1976	26	18	14	10	14	11	5	9	4	11	12	14	27	30	23	14	10	16	24	29	27	32	28	21
March 8, 1976																						12	3	9
Mar. 8 & 9, 1976	13	9	13	12	19	12	9	12	0	11	14	17	14	7	0	13	12	12	12	16	15	15	14	14
March 9, 1976	13	20	23	21	22	16	16	15	23	18														
March 11, 1976											18	16	14	13	13	20	18	12	16	15	25	19	19	14
Mar. 11 & 12, 1976	10	10	6	13	24	12	12	8	12	8	9	10	8	10	14	10	17	14	10	10	11	10	11	13
Mar. 12 & 13, 1976	15	13	12	6	14	17	15	14	15	12	0	13	15	17	16	22	17	14	16	24	22	19	31	31
March 13, 1976	37	29	26	22	28	29	20	19	25	28														
Mar. 29 & 30, 1976					19	8	17	17	13	18	18	14	16	18	10	11	14	14	14	14	14	12	6	6
Mar. 30 & 31, 1976	3	2	2	0	17	12	10	17	0	11	16	10	6	0	0	11	8	9	8	6	9	8	9	9
March 31, 1976	10	9	8	8	7	7	8	15	14	10														

TABLE 13

RECORDED WIND SPEEDS AT 3M ABOVE GROUND 1975 - 1976

All Values Are In Miles Per Hour

Hours of Day	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Nov. 10, 1975																						12	8	10
Nov. 10 & 11, 1975	10	14	12	12	12	10	16	27	38	45	57	66	32	47	35	38	40	49	42	37	39	49	34	34
Nov. 11 & 12, 1975	26	33	38	26	17	20	30	29	38	40	47	47	41	43	42	28	23	21	23	11	10	6	8	9
Nov. 12 & 13, 1975	10	10	8	8	5	5	6	7	5	6	5	6	8	10	7	9	19	10	12	13	13	13	13	5
Nov. 13 & 14, 1975	3	4	9	5	7	7	8	9	7	9	11	10	7	7	9	5	9	9	6	6	9	7	7	5
November 14, 1975	21	20	19	17	11	8	10	10	6	6														
Jan. 21 & 22, 1976				9	7	8	8	6	6	5	9	6	7	9	12	9	9	17	34	36	24	23	36	31
Jan. 22 & 23, 1976	39	25	26	14	25	17	8	14	17	19	12	17	39	40	26	19	14	20	35	40	38	43	40	32
January 23, 1976	36	36	37	20	19	33	27	30	24	21														
March 8, 1976																						6	4	4
Mar. 8 & 9, 1976	6	11	7	9	7	7	4	6	4	5	5	6	9	7	5	4	3	11	19	22	25	21	18	14
March 9, 1976	19	30	35	27	39	23	24	24	34	30														
March 11, 1976											7	4	13	17	21	26	26	19	12	25	36	30	26	18
Mar. 11 & 12, 1976	18	16	9	21	31	16	16	14	14	10	14	12	12	16	12	13	10	11	5	13	10	10	10	10
Mar. 12 & 13, 1976	6	9	7	8	8	7	10	10	6	6	5	8	9	6	20	26	22	18	23	37	32	26	43	43
March 13, 1976	48	40	41	30	40	37	29	25	34	36														
March 29 & 30, 1976						6	11	7	6	7	7	8	8	6	7	9	15	10	19	21	20	15	11	8
March 30 & 31, 1976	3	3	4	0	23	21	14	6	4	6	5	5	3	0	4	5	11	15	13	10	12	12	15	14
March 31, 1976	16	15	16	12	11	12	8	11	14															

TABLE 14

Conditions preceding the event: 16.6 mm. of precipitation fell during the two days leading up to the event. Air temperature was steady at + 4 degrees C and the soil temperature was + 4 degrees C at -2 cm. and + 9 degrees C at -5 cm. The relative humidity was intermediate at 60% and winds were moderate (1 mph at +3m. and 8 mph at 0.5 m., winds at this time are examined later in the report).

Onset of heave: At 2200 hrs. on November 10, the air temperature and the interface temperature dropped as wind increased; at 0100 on November 11 the wind speed exceeded 50 mph at 3 m. and the air temperatures dropped to below 0 degrees C. The interface temperature was lowered to 0 degrees C and heave started immediately.

During the heave event: The soil temperature gradient between -2 and -5 cm. remains constant but increased between the surface and -2 m. The air temperature at 15 cm. remained above 0 degree C.

Settling: After a maximum heave at 0800 hrs., the air temperature rises slightly and this corresponds to a rapid warming up of the interface which reaches + 5 degrees C at 1100 hrs. The gradient of temperatures in the upper 2 cm. of the ground reversed at 0830. The sharp rise in interface temperature is due to incoming solar radiation. Settling of the ground surface to its before-freezing level required 4 hours.

The most significant characteristic of this event is the high winds present during most of it, since it is generally assumed that calm nights are more prone to needle ice growth (e.g. Outcalt, 1969).

b) Event 2, November 11 and 12, Figure 11.

Heave Curve: Event number two is the best record of frost heave

Figure 10

Figure 11

available from Rocky Flats to date. The event lasted 22 hours and heave reached 10.5 mm. at 0700 hrs. on November 12.

Preceding conditions: Only 3 hours separated this event from Event 1, a drop in the air temperature close to the ground corresponded to a similar drop in interface temperature. November 11 was overcast and radiative cooling in the late afternoon probably explain the lowering of the soil temperature. Alternatively, high wind speeds (40 mph) suggest the advection of cool air.

Onset of heave: As in Event 1, heave started immediately after the interface temperature fell below 0 degrees C, at 1600 hrs. on November 11.

During the event: The interface temperature remained below freezing and at the end of the period, the freezing plane was at -2 cm. while the soil temperature at -5 cm remained above +5 degrees C. Wind speeds were high, up to 47 mph.

Settling: Early on November 12 (0600 hrs), the wind speed was reduced and temperatures rose but it required 6 hours for the soil surface to settle back to its normal unfrozen level. The temperature gradient in the upper 2 cm. of soil reversed at 0830 hrs.

c) Event 3, November 12 and 13, Figure 12

The heave curve was very similar to that of Event 2. Heave lasted 17 hours and reached 8.7 mm. 14 hours after it started. The conditions preceding the event show a very rapid cooling of the air (15 cm) and interface temperatures. The rate of cooling was more rapid than that during Event 2 which influences the rate of surface heaving. During the event, wind speed was low (less than 10 mph) and relative humidity decreased to 25%. The soil temperatures at -5 and -2 cm. were remarkably constant but

Figure 12

air temperatures remained above 0 degrees C and increased during most of the event. The interface temperature rose to 0 degrees C at 0700 hrs. and this, in conjunction with high air temperatures, marked the end of surface heaving. The reversal of heat gradient in the upper 2 cm. occurred at 0830 hrs. The high rate of warming explains the rapid return to normal ground surface (3 hours).

d) Event 4, November 13 and 14, Figure 13

This short (6 hours) event was of low amplitude (less than 4 mm.) and was the last one of the mid-November period. No moisture had fallen since November 11 and a rising air temperature account for the cessation of heave activity. The interface temperature was negative two hours before the onset of heave and the upper soil temperature profile reversed outside the heave period. This indicates less than ideal heaving conditions. This event is typical of the late frost cycles at the end of a freezing period. Radiative cooling of the interface under clear sky and calm wind conditions can be expected when the cold, moist air mass responsible for a needle ice period is replaced by warmer and dryer air.

e) Event 5, January 21 and 22, Figure 14

The ground was only moderately wet during the January freezing period (6.9 mm. water equivalent; 2 days prior to the event) and the heave response to negative interface temperature was not immediate. The heave event lasted 16 hours and had a low amplitude (2.8 mm.). The needle ice growth took place during the first hours of frost; around 3:00 a.m. on January 22 the freezing plane dropped and massive frost occurred; the ground froze at least to -2 cm. This explains the stable heave ceiling visible on the heave curve. Around 0900 hrs., high winds and the rising of the sun brought a gradient reversal in the upper soil and the warming

Figure 13

Figure 14

up of the interface. The return to normal surface was slowed down by the depth of the massive frost and took 5 hours. The low interface temperature necessary for heave was caused by radiative cooling in a dry atmosphere.

f) Event 6, January 22 and 23, Figure 15

This event is very similar to the preceding one. The heave cycle lasted 16 hours and the amplitude was 3.1 mm. Radiative cooling of the interface in dry air was the cause of the needle ice growth (air temperatures were positive). The wind was irregular during the cycle and its warming effect on the interface is visible in Figure 15. When the freezing plane moved downward (around 2:00 a.m.) the heave ceased; at 0830 hrs. the reversal of soil temperature gradient and a positive interface temperature induced a rapid return (2 hours) to normal surface level. The maximum of heave recorded occurred exactly when the freezing plane started to move downward at 0200 hrs.

g) Event 7, March 8 and 9, Figure 16

Event 7 is the first cycle of the third heave period. A fairly large amount of precipitation fell before the period (16.2 mm.) but the amount of heave recorded was fairly small (around 5 mm.). Two explanations are possible: 1) the slow rate of precipitation (see Figure 9) permits too much evaporation and percolation and does not lead to soil saturation or 2) the vegetation begins to have a limiting effect on needle ice growth. The effect of the vegetation was visible in the wind record as an inversed velocity gradient (this could possibly indicate a higher level of turbulence close to the ground). Event 7 had a duration of 16 hours and an amplitude of 5.2 mm. Heave started when the interface temperature dropped

HOURLY VALUES OF SEVERAL PARAMETERS DURING THE HEAVE EVENT OF JANUARY 22 AND JANUARY 23, 1976

Figure 15

HOURLY VALUES OF SEVERAL PARAMETERS DURING THE HEAVE EVENT OF MARCH 8 AND MARCH 9, 1976

Figure 16

below 0 degrees C. and increased until rising air temperature induced a warming of the interface above 0 degrees C. The upper soil gradient reversed at 0800 hrs. and return to normal conditions took 3 hours.

h) Event 8, March 11 and 12, Figure 17

The duration of this cycle was 13 hours and its amplitude only 1.6 mm. During this event, the air temperature was very cold (-15 degrees C), probably giving a rate of heat loss from the soil surface too great for good needle ice development. Heave started shortly after the interface froze but the very cold air temperature retarded the upper soil gradient reversal until after the heave cycle had ended. Very high temperatures during March 11 (the interface reached +35 degrees C) were felt at -5 cm. depth and the soil did not freeze to -2 cm. when the air temperature was at -15 degrees C. The relative humidity was high (cold air) and the winds moderate during the event.

i) Event 9, March 12 and 13, Figure 18

Heave lasted 18 hours and reached 5.1 mm. The air temperature (screen) between events 8 and 9 remained below -10 degrees C, but the soil/atmosphere interface temperature reached +10 degrees C at 1400 hrs. (March 12). At 1630 hrs. the interface froze and heave started almost immediately. Heave stabilized at about 5 mm. until 0200 hrs., when the freezing plane was at -2 cm. and remained there until 0700 hrs. Then, higher winds and rapid warming of the air and the ground induced thaw and a rapid return to normal surface level. The temperature gradient in the upper soil reversed at 0800 hrs. and melting took only 2 hours.

Figure 17

Figure 1A

j) Event 10, March 29 and 30, Figure 19

Events 10 and 11 represent two of the heave cycles of the fourth and final frost heave period of 1975 - 1976. This period was preceded by a relatively large amount of snow (13.3 mm. water equivalent on March 28 and 29) and a cold air temperature. Event 10 occurred when only a small portion of the snow had melted and little water was available in the soil for needle growth. The cycle lasted only 9 hours and heave reached only 2 mm. Because of a lack of water in the soil, the heave response to interface freezing and thawing was delayed at both ends of the cycle (a 2 hour lag at the start of the cycle). Inversion of the wind speeds in this and the following event probably reflected the increased roughness of the vegetation. The soil temperature gradient between -2 and -10 cm. remained constant during the event, which suggests the damping influence of the snow cover.

k) Event 11, March 30 and 31, Figure 20

This cycle lasted 13 hours and gave 7 mm. of heave. Relatively high air and interface temperatures on March 30 were associated with snowmelt which made more water available for needle ice growth than on the preceding night. The onset of the heave was again lagged two hours behind the freezing of the interface. Needle ice development terminated at 0600 hrs. when the air temperature close to the ground, rose above 0 degrees C. The rapid increase in air/ground temperatures induced a fast return to normal surface level (3 hours). The relationship between events 10 and 11 is typical of needle ice development immediately after the moving of a cold, moist air mass into the Colorado Piedmont. It takes about one day for sufficient moisture to be transferred from the snow cover

Figure 19

Figure 20

into the soil to permit good needle ice growth in the snow free areas.

SUMMARY

The 33 frost events recorded at Rocky Flats in the 1975 - 1976 winter occurred in 4 groups of consecutive days, referred to here as 'frost heave periods.' Each of these periods seems to have been associated with a single weather pattern which starts with the dominance of a cool, moist air mass over the Colorado Piedmont. This has not, however, been verified by an examination of the synoptic patterns of the winter and so needs further evaluation.

The winter record shows a greater frequency of needle ice occurrences in the late fall and early spring with heave being particularly important after intense precipitation (e.g. in November). In all cases, the soil remained unfrozen at 5 cm. depth during needle ice events, and surface lifting usually ceases when the freezing plane extends to 2 cm. depth. This seems true whatever the soil surface or air temperature.

11 of the 33 cases recorded have been examined in detail and show considerable variety, in both the environmental conditions under which they occur and the soil responses to them. The duration of heave varied between 6 hours and 22 hours and the amount of heave, between 1.6 mm. and 10.5 mm. The timing of greatest heave was, however, quite constant: within an hour of 0700 hrs. in all cases but one. The onset of surface heave is clearly related to freezing temperatures at the soil surface, to which it usually responds immediately. In some cases, heave may also be associated with air temperatures below 0 degrees C (e.g. Event 1) while in other cases the air temperature remains above freezing (e.g. Event 6).

During 6 of the 11 events examined in detail, wind speeds in excess of 20 mph were recorded during needle ice growth and on one occasion the wind reached 66 mph during a frost event (Event 1). This seems to be at variance with the findings of other workers who emphasize the need for relatively still air conditions during needle ice development.

SIMULATION MODELLING OF NEEDLE ICE EVENTS

To the present (May, 1976), most of the effort in computer simulation modelling has been expended in adapting existing routines to the University of Colorado CDC 6400 system and translating magnetic tapes containing needed meteorologic data. This part of the report includes only a brief description of the two simulation models which are presently being evaluated for their applicability to the Rocky Flats situation.

The most basic model under consideration is that developed by Outcalt (1969) and is based upon the energy conservation equation for the ground surface. This model requires meteorologic data and site characteristics as input and provides as output the normal energy budget components for the surface as well as a soil temperature profile. In these estimations, the soil is treated as a homogeneous conducting medium and the flux of water and water vapor are ignored. Because water movement is not treated explicitly, this model will probably only serve to indicate when thermal conditions in the soil would be conducive to frost heave and needle ice growth.

Outcalt and Carlson (1974) describe a simulation model for the coupled flow of heat and water in the soil which is also being fitted to the Rocky Flats situation. This model should allow the prediction of frost heave magnitudes since it allows the inclusion of fluxes of water and water vapor through the soil and of phase changes in the water. The meteorologic inputs to this model are similar to those required in the first but it does require better estimation of soil characteristics,

particularly as these relate to water relations in the soil. Originally this model was designed to simulate situations in which the water table was close to the ground surface. This is not the case in the interfluvial areas at Rocky Flats that are of most interest in this project. There, the water for segregation ice development frequently derives from recent snowmelt and so much effort has gone into incorporating this in the model.

The input data needed for both of these models includes the soil characteristics of the Lindsay Ranch site (already known) and meteorologic data, mainly wind and solar radiation, which is routinely collected at the site or at the Rocky Flats plant. Model verification is to be based upon the observed occurrences and magnitudes of frost heave and the measured soil temperatures (described earlier).

WIND STUDIES 1975 - 1976

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 1975 - 1976. These observations are made for two reasons: first, to estimate the influence of air movement on needle ice development; and second, to evaluate the potential for soil erosion by the wind at Rocky Flats. The first of these was examined earlier in this report, the second is of concern here.

The Mean Wind Profile

The characteristics of air flow that are of interest in soil erosion may be estimated from measured wind speeds at two heights above the ground by use of the logarithmic velocity profile (Sutton, 1949; Plate, 1971). This model is widely used but its validity depends upon

a number of assumptions which cannot always be met. In particular, it requires that the air flow be turbulent (with a high Reynold's Number), involve a boundary layer that is neutrally stable and move over a surface that is aerodynamically rough. Since relatively high wind speeds are required for particle entrainment, these three assumptions are probably reasonable in this part of the study. A further requirement, for a uniform surface upwind of the point at which measurements are made, may not be met so well. The interfluvial surface to the west and northwest of Plot B on the Lindsay Ranch site is almost flat and uniform for between 100 m. and 200 m., sufficient for the development of the logarithmic profile to the level of the highest anemometer. However, it is doubtful if winds from other directions would meet the requirements because of topographic changes to the east and southeast.

Two characteristics of interest to the study of wind erosion can be estimated from the wind profile averaged in the time domain. Since both are estimated from temporal averages of wind speed, they cannot be simply applied to situations involving the movement of single soil particles; only to movement in bulk or on average. Individual particles will be especially responsive to turbulent effects (e.g. the variance in velocity illustrated by Figure 21) that are not easily fitted into a mean profile (Lyles and Woodruff, 1972). The two characteristics are the roughness length (Z_0) and the friction velocity (V_*). The first of these is a characteristic of the surface over which the flow occurs and is estimated by the elevation at which the wind velocity tends to zero. V_* provides an estimate of the horizontal shearing stress in the moving fluid and so, with the common assumption that the shearing stress is independent of height above the ground, of the stress it exerts

on the underlying surface. Since they are estimated from only two points on velocity profile, both Z_0 and V_* cannot be evaluated precisely here.

With anemometers at 50 cm. and 300 cm., Z_0 is derived as:

$$\log Z_0 = \frac{1.7 V_{300} - 2.477 V_{50}}{V_{300} - V_{50}}$$

where Z_0 is the height of zero velocity (cm) and V_i is the wind speed at height i . With the same instrumental arrangement, V_* is approximated (to $\pm 2\%$) as:

$$V_* \approx 0.1 (V_{300} - V_{50})$$

where V_* (the friction velocity) has dimensions of $M. sec^{-1}$ and V (wind speed) is measured in miles per hour.

The Roughness Length

A preliminary examination of wind records for 1975 - 1976 suggests that Z_0 is almost invariant through the winter period and averages between 5 and 10 cm. for the interfluvial surface at the Lindsay Ranch site. This is the same magnitude as estimates of Z made elsewhere over long grass covered surfaces (e.g. Sutton, 1949, p. 107; Geiger, 1965, p. 275). The lack of temporal changes in Z_0 needs further testing but it is important because it does not conform to a seasonal change in the appearance of the vegetation. A roughness length of more than 5 cm. suggests that soil particles are unlikely to be exposed to wind influences on the Lindsay Ranch site, even on the patches of bare soil exposed in the interfluvial area. At this scale, the vegetation cover controls the aerodynamic quality of the surface although that may not be true of the entire area

of Rocky Flats, particularly in those parts where the soil is exposed more extensively.

Initial estimates of Z_0 above a snow cover suggest a much smoother surface. Under these conditions, the roughness length is often reduced to less than 4 cm., as for example on November 10 (Figure 21 and 22). This smoothing is also associated with a 'lifting' of the effective ground surface by the thickness of the snow cover which suggests that the roughness length is in fact overestimated. This could account for the difference between the values shown in Figure 22 and those quoted in the literature for a snow cover ($Z_0 = 1$ cm.). The difference in topographic roughness which a snow cover produces is an important reason why snow entrainment into an air flow cannot be used as more than an approximation of soil entrainment. In addition to the difference in particle density, the erosion of snow occurs from a smoother surface (where the aerodynamic influence of the vegetation is much reduced) than does soil erosion.

The Friction Velocity

The amount of shear in the air flow obviously varies widely with the absolute wind speed (also illustrated for a single case in Figure 22). By itself V_* is only important when related to the soil particles at the ground surface and so it is useful to introduce the concept of a critical friction velocity (V_{*c}). This is the shear at which the soil particles exposed at the surface may become unstable, and so entrained into the air flow. The concept of such a critical threshold has been criticised because it is estimated from mean velocities whereas actual particle entrainment is most likely to be a response to velocities in turbulent eddies

Figure 21 EXAMPLES OF WIND VELOCITIES AT 3m AND 0.5m (November 10, 1975)

Figure 22 WIND CONDITIONS: NOVEMBER 10, 1975.

(Lyles and Woodruff, 1972). Nevertheless, it offers a first approximation of the probability of wind erosion which is useful if not pressed. If ϕ_{20} , the particle diameter which is exceeded by 20% of the surface soil, is defined as a controlling particle size, on the assumption that finer particles will be protected from erosion by coarser ones.

(This assumption may not be a good one in an environment in which frost action is effective in disturbing the soil and bringing fine material to the surface). On Plot B at the Lindsay Ranch site, ϕ_{20} is approximately 2 mm. which suggests a threshold shear velocity of 0.65 m. sec^{-1} (Bagnold, 1944, p. 88). This is equivalent to a velocity difference of about 6 1/2 mph between the anemometers at 300 cm. and 50 cm. above the ground at Plot B, not a great difference. In the 224 days of record for the 1975 - 1976 winter, this threshold was exceeded for at least 10 min. on 75 days (i.e. on 1 day in 3). There is, however, no evidence on the Lindsay Ranch site of sand transport and erosion which this analysis would suggest could occur frequently. The discrepancy is explained by the controlling influence of the vegetation cover and the magnitude of Z_0 .

SUMMARY

In summary, two points emerge from a preliminary examination of wind conditions on the Lindsay Ranch site. Both require further, more comprehensive analysis of the wind record for 1975 - 1976. First, estimates of the roughness length for the site suggest that little of the soil surface on the site is exposed to wind erosion. In a situation where the bare patches of soil are usually less than 1/2 m. across and the vegetation is up to 30 cm. high, this is not surprising. Second, wind

shears capable of entraining the soil into motion, if it were exposed sufficiently, are quite common at the Lindsay Ranch site. During 1975 - 1976, one day in three experienced a friction velocity in excess of that required to move particles of 2 mm. size and so it is to be expected that such winds could follow needle ice events by no more than a week. This conclusion corroborates that shown in the earlier analysis of wind records from the Rocky Flats Plant (Caine and Morin, 1975) which defined the probability of winds over 40 mph at about 0.25 during the winter months (i.e. one day in four).

CONCLUSION

The objective of this report has been to describe and summarize the observations made on Rocky Flats during the winter of 1975 - 1976 as part of a study of ground freezing and surface soil erosion. This description is to be followed at a later stage by a more analytical examination of the data presented here.

During the broad scale studies of the entire Rocky Flats area, progress has been made through the study of surface soil textures to the point at which the mapping of needle ice potential can be completed. The topographic controls of soil textures at and close to the soil surface which have been identified here provide the basis for this. There remains, of course, the need for some further field checking of the results obtained by such indirect evaluations, especially in parts of the Rocky Flats area which are far removed from the area on which the method

is based. There is also a need for a further evaluation of the match between potential and actual frost influences and for the comparison of these with other environmental characteristics of Rocky Flats. This is planned for the coming year.

During 1975 - 1976, soil heave and/or needle ice development has been observed or recorded on 33 days at the Lindsay Ranch study site, often on consecutive days. This first complete winter of records supports the contention that this study was initially based upon: that needle ice development is a fall and spring phenomenon. Despite a relatively dry spring in 1976, the empirical record bears this out and is consistent with the pattern found in observations made during the previous winter.

The needle events described here illustrate a wide variety of condition and responses during surficial (2 cm.) ground freezing. Both the amounts and durations of surface heave show considerable variability, although the time of greatest heave is relatively constant (about 0700 hrs.) throughout the winter. Two other observations worthy of further testing are of interest; one is that surface heave has occurred with air temperatures above freezing point; the other, that needle ice development has been associated with relatively high wind speeds up to 66 mph.

Analysis has recently commenced of the wind records from the study site with a view to estimating erosion potential in association with needle ice development. Initially, this suggests that there may be little erosion potential where the present vegetation cover is maintained but that removal of the vegetation could certainly expose soil material to

wind conditions capable of producing erosion.

For the remainder of the present support period, work on this project will be concentrated on a more substantive analysis of the information derived from the 1975 - 1976 winter and the comparison of it with the less comprehensive record from the preceding winter. This should be completed as a further progress report by October, 1976. Three lines of inquiry are expected to be included in that later report:

1. An extension of the mapping program in that later report; to the entire area of Rocky Flats, including validation of the procedures and criteria in use.
2. A more rigorous analysis of the environmental conditions associated with frost heave of the soil surface at the Lindsay Ranch site and the fitting of simulation models to the.
3. The complete analysis of the entire winter record of conditions at the study site, on a more coarse time interval than that involving needle ice events. One reason for such an analysis is to search for periods when weather conditions appear favorable for needle ice development but none was recorded or observed.

ACKNOWLEDGEMENTS

We should like to acknowledge the assistance provided this project by personnel at the Rocky Flats plant, particularly by members of the Environmental Sciences and Waste Control Group under Dr. M.A. Thompson. Our work has also benefitted immeasurably from the assistance of John Clark (field instrumentation) and Rolf Kihl (lab. analyses) and from the counsel of Carol Jenner and Sam Outcalt. Last, but not least, are the undergraduate assistants who did the work: Jan Cassin and Clifton Mitchell.

REFERENCES

- Bagnold R. A., 1944: The physics of blown sand and desert dunes.
Methuen. Pp. 265.
- Beskow, G., 1935: Soil Freezing and Frost Heaving with Special Application
to Roads and Railroads. Swed. Geol. Soc. Yearbook 26; 145 pp.
- Caine, N. and P. Morin, 1975: The significance of Frost Action and Surface
Soil Characteristics to wind erosion at Rocky Flats, Colorado. First
Progress Report to ERDA E(11-1)-2517-1; 66 pp.
- Chepil, W.S. and N.P. Woodruff, 1963: The Physics of Wind Erosion and Its
Control, Advances in Agric. v.15; p. 211 - 302.
- Fahey, B.D., 1973: Seasonal Frost Heave and Frost Penetration measurements
in the Indian Peaks of the Colorado Front Range, Arctic and Alpine,
v. 6, N. 1.
- Farmer, E.E., 1973: Relative Detachability of Soil Particles by simulated
Rainfall, Soil Sci. Soc. Amer. Proc., v. 37, pp. 629 - 633.
- Lyles, L. and N.P. Woodruff, 1972: Boundary - layer flow structure:
Effects on detachment of noncohesive particles, in H.W. Shen (ed)
Sedimentation, symposium to honor Prof. H.A. Einstein; Water Resource
Publications, Fort Collins, Colorado, pp. 2-1 -- 2-16.
- Outcalt, S.I., 1969: Weather and Diurnal Frozen Soil Structure at
Charlottesville, Virginia, Water Res. Res. 5:6, pp. 1377-1382.

Outcalt, S.I., 1970: A Study of Time Dependence During Serial Needle Ice Events, Arch - Met Geoph. Biokl., 4, 19, pp. 329-337.

Outcalt, S.I., 1971: Field Observations of Soil Temperature and Water Tension Feedback Effects on Needle Ice Nights, Arch - Met Geoph. Biokl., A 20, pp. 43-53.

Outcalt, S.I. And J.H. Carlson, 1975: A Coupled Soil Thermal Regime Surface Energy Budget Simulator, (Unpublished).

Taber, S., 1930: The Mechanics of Frost Heaving, Jour. Geol. v. 38, pp. 303-317.