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

First Progress Report

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ABSTRACT

This is the report of the first period of study of soil-frost effect on Rocky Flats. Two lines of work have received attention in this period.

On a broad scale, a program of mapping has been started which will be expanded to cover the entire Rocky Flats area. The initial work suggests that soil frost susceptibility can be keyed quite well to topographic and vegetation characteristics. On the same scale, the study of past weather records from Rocky Flats supports the hypothesis that the early spring period is probably the one with greatest frost activity in the area. This is also the period when most significant needle ice development was observed in 1975.

On a site-specific scale, instrumental observations of meteorologic conditions and soil responses to freezing have been initiated on a site near the Lindsay Ranch on Rocky Flats. Soil freezing events have only been adequately recorded in the period after March 1, 1975; prior to that date, no needle ice growth has been recorded, although that may be due to a lack of instrumentation rather than of favorable conditions. Observation made after March 1 suggests that needle ice development on Rocky Flats is a response to the same environmental controls as elsewhere. This should facilitate modelling the process of freezing and thawing.

INTRODUCTION

This is the first progress report of a study of soil-frost effects and wind erosion on Rocky Flats, Colorado. It has been prepared after six months of work, including the latter part of the 1974-1975 winter which presented an opportunity to initiate observations and measurements in the field. Since it is expected that the study will continue through 1976, this initial period of work has been used in a reconnaissance manner. It has served to test procedures and instrumentation and to sharpen the definition of objectives to be used in the 1975-1976 winter.

The Problem

In general, the study is concerned with evaluating the possible interactions between frost action in the soil of the Rocky Flats area and later soil removal by wind erosion. This interaction may provide a resuspension mechanism by which plutonium in contaminated soil is dispersed downwind. A mechanism of this type is suggested by the empirical observation of the seasonal fluctuations of Pu concentration with freeze-thaw activity and wind action (Figure 1).

Three parts to this problem have been identified and will be treated separately. They are:

1. Broad-scale studies which include the mapping of soil frost susceptibility on the Rocky Flats site; the study of snowdrift patterns on the site (as a surrogate for wind-moved sediment and a source of moisture for freezing), and the study of climatic records to establish frost and high wind probabilities for the area.

2. Detailed studies of soil freezing and wind effects on site 200 m west of the Lindsay Ranch on Rocky Flats.
3. Simulation modelling of soil freezing events and wind shear to allow more confidence in the extrapolation of empirical studies.

This report treats each of these in turn, with greatest emphasis being given to the second which has received most attention in the past six months.

Calendar

Work on Rocky Flats started in late October 1974 with reconnaissance surveys and a search for a detailed study site. The Lindsay Ranch site (described below) was chosen and a varying record of observations and measurements maintained on it from late November. The type of observations and the period over which they were made are summarized in Table 1. In general, there has been an upgrading in the number of characteristics observed and the precision of measurements during the winter. Observations ceased on April 15.

In addition to the instruments listed in Table 1, a light trailer for personnel and recorders was installed on the site in early 1975, and the upper part of the study site was fenced to minimize damage. The fence around the study area will be completed at a later time.

Personnel

The following personnel have been employed on this project in the period October 1974-June 1975:

Nel Caine - Principal Investigator, 15% time.

Table 1

CALENDAR: LINDSAY RANCH SITE 1974-1975

<u>Observation</u>	<u>Period</u>	<u>No. of Plots</u>	<u>Form</u>	<u>Precision</u>
Air Temperature	12.4 - 4.15	1	Continuous	$\pm 1^{\circ}\text{C}$
Air Humidity	12.4 - 4.15	1	Continuous	$\pm 3\%$
Precipitation	12.12 - 4.15	1	Continuous	$\pm 1 \text{ mm}$
Soil Temperature				
Depth 0 cm	3.14 - 4.15	2	Continuous	$\pm 0.25^{\circ}\text{C}$
2 cm	12.4 - 4.15	3	Cont./Periodic	$\pm 0.5^{\circ}\text{C}$
5 cm	12.4 - 4.15	5	Periodic	$\pm 0.5^{\circ}\text{C}$
10 cm	12.4 - 4.15	5	Periodic	$\pm 0.5^{\circ}\text{C}$
20 cm	12.4 - 4.15	4	Periodic	$\pm 1.0^{\circ}\text{C}$
Soil Moisture				
5 cm	1.23 - 4.15	5	Periodic	$\pm 5\%$
10 cm	1.23 - 4.15	5	Periodic	$\pm 5\%$
20 cm	1.23 - 4.15	5	Periodic	$\pm 5\%$
Soil Heave	3.20 - 4.15	1	Periodic	$\pm 5\%$
Wind Speed	3.20 - 4.15	1 (2 hrs.)	Periodic	$\pm 2 \text{ m sec}^{-1}$

John Clark - Instrumentation Technician, ca. 1 month equivalent.

Rolf Kihl - Laboratory Technician, ca. 1 month equivalent.

Pierre Morin - Graduate Research Assistant, 50% time.

In addition, approximately 35 man-days of technician time in the Electronics Shop, Physics Department, University of Colorado, have been spent in recorder interface design and manufacture. Dr. S. I. Outcalt, University of Michigan, has made three visits to Boulder in connection with this project.

In the next three months, it is expected that Morin will be employed full-time on this project and that Caine will spend one month in analysis and field work. Further technical and field assistance will also be required in soil analysis and mapping and in field preparation for the 1975 winter.

BROAD-SCALE STUDIES

Two sub-programs have been included under this heading: those involving a relatively long time period (the past six years) and those involving a larger spatial scale (the entire Rocky Flats area). The aims of this part of the project are to define the potential for frost action and wind erosion in a time scale which is longer than that of the study itself and to estimate the susceptibility of the surface soil to frost action and erosion across a wider area than a single study site.

Historical Record

Initially, this analysis has been made by defining for a number of

meteorological events a series of probabilities:

$$P_1 = m_1/N_1 \quad (1)$$

where m_1 is the number of occasions on which the event 1 has been recorded, and N_1 is the number of days in that record. Thus the probability of a frost in April might be defined empirically from the number of recorded frosts and the total number of days in the record for April. In the present work, the record used is that for six years (1969-1974) at the Rocky Flats Plant. In using Equation (1), the effects of the lack of stationarity in climatic time series have been ignored and, in extending it to conditional probabilities, the independence of different records is assumed. Both of these assumptions may require further consideration at a later stage.

The six years of record have been analyzed for (a) freeze-thaw events, each defined as a complete cycle above-below-above freezing temperatures; (b) daily precipitation in excess of 0.01 inches, and (c) wind speeds in excess of 40 m.p.h. (18 m sec^{-1}). The first two of these have also been combined in the characteristic of "freeze-thaw events immediately following precipitation" (i.e., within 24 hours). The results are summarized in Table 2 on a monthly and semi-monthly basis and a smoothed profile of column (5), the product of the freeze-thaw after rain and the high wind probabilities, is shown in Figure 1. The results clearly show a bimodal pattern in the frequency of frost events on Rocky Flats, although this is not so evident as at higher elevations in this part of Colorado. The mid-winter period is one of relative quiescence, presumably when the air temperature remains below freezing for some days at a time, and most frequent activity tends to occur on either side of this period. When this is combined

Table 2 EMPIRICAL PROBABILITIES OF FROST-WIND ACTION: ROCKY FLATS

<u>Month*</u>	(1) <u>Freeze-Thaw</u>	(2) <u>Precip.</u>	(3) <u>Wind</u>	(4) <u>Freeze-Thaw after Precip.†</u>	(5) <u>Product (3) x (4)</u>
Jan 1	0.27	0.10	0.46	0.01	0.005
2	0.42			0.03	0.014
Feb 1	0.54	0.12	0.24	0.07	0.017
2	0.64			0.09	0.022
Mar 1	0.35	0.24	0.25	0.03	0.008
2	0.44			0.09	0.022
Apr 1	0.30	0.24	0.22	0.10	0.022
2	0.22			0.09	0.020
May 1	0.07	0.23	0.14	0.03	0.004
2	0.0			0.0	0.0
Jun 1	0.0	0.21	0.14	0.0	0.0
2	0.0			0.0	0.0
Jul 1	0.0	0.33	0.06	0.0	0.0
2	0.0			0.0	0.0
Aug 1	0.0	0.18	0.06	0.0	0.0
2	0.0			0.0	0.0
Sept 1	0.0	0.22	0.11	0.0	0.0
2	0.08			0.07	0.008
Oct 1	0.13	0.23	0.13	0.08	0.010
2	0.19			0.07	0.009
Nov 1	0.37	0.19	0.25	0.08	0.020
2	0.52			0.05	0.012
Dec 1	0.35	0.11	0.35	0.03	0.010
2	0.54			0.04	0.014

* Months are divided into two parts at the 15th.

† Freeze-thaw after precipitation is defined by more than 0.01 in. of precipitation in the 24-hour period immediately preceding a freeze-thaw event. No account of the nature of the precipitation is taken.

Figure 1 FROST CONDITIONS AND AIRBORNE PLUTONIUM CONCENTRATIONS

with the precipitation and wind effects (columns (3) and (4) in Table 2), the result shows a maximum in spring which exceeds the late fall maximum. This is also the time when snow melt might be expected to contribute to soil moisture recharge and thus enhance the effectiveness of soil freezing. The correspondence of this pattern with that of airborne radioactivity found in 1972 and 1973 (Figure 1) corroborates the original hypothesis on which this study was based. A test which is based on air temperatures and time periods of at least two weeks length is not, however, a satisfactory one for a hypothesis which suggests ground level effects on a time scale of 12 hours. For this reason, it will be given little further attention.

Spatial Record

In considering a wider spatial area than a single detailed study site, two criteria are being considered: the susceptibility of the Rocky Flats soils to surface frost action and the distribution of snow over the area. The second of these is included for two reasons: because snowmelt influences soil moisture recharge and so contributes to the effectiveness of soil freezing and thawing in the spring, and because wind transported snow may be used as an easily traced analog of wind eroded soil. It should allow at least the definition of probable areas of deflation and deposition.

To the present, soil sampling has only been conducted on the northwestern part of the Rocky Flats site (including the Lindsay Ranch study site). A textural analysis of samples from the Lindsay Ranch site, with the frost susceptibility criterion of Beskow (1935), is shown in Figure 2. The sequence A through F represents the series of study plots down the slope profile and seems also to represent a continuum of increasing frost susceptibility.

The samples from the interfluvial surface of the Rocky Flats pediment gravels consist of silty sand with less than 20% clay. With distance downslope, a textural change occurs which is most marked in the size fraction greater than 2 mm. This may reflect an admixing of material derived from the underlying Pierre Shale of the valley sides or a reduced transport of the coarse particles by comparison to the finer fractions. In any case, the increase in the estimated soil frost susceptibility seems to occur in parallel with a soil drainage condition which may lead to higher soil moisture levels as the valley floor is approached. Measured field capacity of these soil samples increases from about 50% to slightly over 60% by weight in the same direction (Table 3).

A textural analysis of 40 samples is summarized in Figure 3. Most of these samples come from the upper 5 cm or less of the soil in the northwestern part of the Rocky Flats site (around the Lindsay Ranch). They show the clear difference in soil texture (hence, frost susceptibility) between the valley floor areas and the interfluvies between the valleys. This contrast also appears in other characteristics related to the frost potential and erodibility of the soils from the two topographic situations (Table 3) and in their moisture tension characteristics.

It is planned to expand the sampling network over the Rocky Flats area during the summer 1975 with the aim of allowing a map of frost susceptibility to be produced by the end of the year. This will not be difficult since the moisture retention characteristics and frost susceptibility of the soils are clearly related and are also related to the underlying material and the topography.

Actual testing of frost susceptibility under controlled conditions

Figure 2 SURFACE SOIL TEXTURE: LINDSAY RANCH SITE

Table 3

SOIL CHARACTERISTICS: ROCKY FLATS

	<u>Hygroscopic Moisture</u>	<u>Specific Retention</u>	<u>Fraction > 0.25 mm</u>	<u>Organic Content</u>
Pediment Gravels	1.6%	46.7%	33.4%	6.9%
	1.6	47.6	28.1	7.2
	1.4	49.2	29.4	6.1
	1.4	49.3	32.5	6.7
	1.9	65.4	28.8	10.9
	1.2	42.0	41.4	5.1
	1.2	54.2	32.4	6.4
Lower Slopes and Valley Floors	1.4	60.1	23.6	6.1
	2.5	61.0	13.1	6.3
	2.4	64.0	?	9.2
	1.8	56.2	?	6.1
	2.8	78.8	(30.2)	11.6
	3.2	68.4	(35.7)	12.2
	3.0	79.6	(22.7)	12.0

Figure 3

TEXTURE TRIANGLE: ROCKY FLATS SOILS

with an unlimited supply of water will be made on soil samples in an insulated box with a heated water reservoir at its base. This will be used in a chest freezer in the manner described by Heidmann (1974) and, during the winter, in the open to allow more "natural" freezing of the soil.

SITE STUDIES

Local studies have been made on a single, southeast-facing hillside immediately west of the Lindsay Ranch on the Rocky Flats site. The observational program of Table 1 has been conducted on six plots distributed along the slope on this site in the 1974-1975 winter.

The Lindsay Ranch Site (Photographs 1 and 2)

The site is located about one-half mile northwest of the Rocky Flats Plant on the north side of the valley in which the Lindsay Ranch is situated and about 200 m west of the ranch. The area of study extends from the pediment surface of the interfluvial to the valley floor, but most emphasis has been given to the interfluvial area where exposed soil suggests greatest potential for frost effects and wind erosion. This emphasis will probably continue.

The topography of the site is quite simple, but seems to be a reasonable "natural" analog of the "hot spot" within the Rocky Flats Plant. A flat, almost horizontal pediment surface (Plots A and B) gives way through a sharp convex change of slope (Plot C) to a relatively straight slope of about 18° (Plot D). At about the contact of the Rocky Flats alluvium with the underlying Pierre Shale, the slope profile becomes concave and gradually flattens in angle to the valley floor. Plots E and F are on this lower

concave segment. At the upper end of the concave segment, a disused irrigation ditch marks the highest level at which material derived from the Pierre Shale is obvious at the ground surface (i.e., the lowest level to which the pediment gravels have moved). The ditch also coincides with a clear change in the vegetation: from disturbed dry pasture upslope to moist meadow downslope of the ditch (Webber, 1975). Close to the creek in the valley floor, the latter becomes a wet *Carex-Juncus* marsh.

The surface soil material (to about 5 cm depth) on the pediment and the upper slope is generally of a silty or clayey sand texture. With distance downslope, it tends to become texturally finer (Figure 2) to form a loam on the lower slope and valley floor. In this, it corresponds to the topographically associated changes found elsewhere on Rocky Flats (Figure 3). The change in surface soil texture is suggestive of an increase in frost susceptibility downslope and this will be compounded by a parallel change in moisture status. Only the vegetation cover, which is almost 100% on the valley floor, acts in the opposite direction. The effect of soil texture on soil moisture relations is also reflected in the soil moisture curves of Figure 4.

In a study of frost effects on soil, the significant features of the Lindsay Ranch site may be summarized as:

1. its topographic similarity to the slope from the pediment surface southeast of the Rocky Flats Plant;
2. the disturbed nature of the surface and soils on the pediment surface, suggesting frost action;
3. the relatively uniform fetch for more than 100 m upwind (northwest) of the study area;

Figure 4 SOIL MOISTURE TENSION CURVES

4. the range of situations available within 100 m of the site which are available for instrumental observation.

THE 1974-1975 WINTER

Table 1 summarizes the range of observations that have been conducted as part of this study on the Lindsay Ranch site. This section briefly describes the nature of the period during which observations were made in that winter. The following section examines in more detail the occasions on which needle ice activity has been observed in the spring of 1975. These occasions are treated in more depth because they are more critical to the hypothesis which the project seeks to test.

Weather conditions on the Lindsay Ranch site during the period December 1974 to mid-April 1975 are summarized in Table 4. During this period, total precipitation was 110.8 mm, for the most part in the form of snow. The monthly totals increase from December (9 mm) to April (24 mm in the first 10 days) and follow the normal seasonal pattern for this part of Colorado (e.g. Table 2). The frequency of rain-days shows the same trend (Figure 5) as well as the daily rainfall totals (a maximum of 16 mm in one day was recorded on April 10).

Snow surveys on the site were made on four occasions during the winter (Table 5). Since these surveys were usually made immediately after storms, the recorded snow density is always low. The snow cover never lasted long on the ground in 1974-1975, although on occasion drift development was observed in the area between Plots C and D (Photo 2). The variability of snow cover duration is suggested by Figure 6. Snowfall seems to have been the ultimate source of the moisture in the upper soil that

Table 4 METEOROLOGICAL SUMMARY: DECEMBER 4, 1974 - APRIL 10, 1975

	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>Period</u>
<u>Monthly Means =</u>						
Max. air temp.	2.8°C	4°C	4.3°C	7.1°C	6.9°C	5°C
Min. air temp.	- 5°C	-7.4°C	- 8°C	-3.5°C	-3.8°C	-5.6°C
Max. R. H.	83.9%	85.1%	81.3%	84.4%	95.6%	86.1%
Min. R. H.	40.5%	34.8%	39.6%	38.6%	45.4%	39.7%
Hrs/day > 0°C	8.2	10.2	11.1	13.6	14.8	11.6
Monthly Precipitation	9 mm	15.5 mm	22.8 mm	39.5 mm	24 mm	110.8 mm
<u>Extreme Values =</u>						
Max. air temp.	13.5°C	14.5°C	14°C	19°C	17°C	19°C (3/20/75)
Min. air temp.	- 17°C	- 22°C	-22°C	-21°C	-18°C	-22°C (1/11;2/5/75)
Max. R. H.	100%	100%	100%	100%	100%	100%
Min. R. H.	14%	5%	16%	6%	22%	5% (1/20/75)
Max. Hrs/day > 0°C	24	24	24	24	24	24
Min. Hrs/day > 0°C	0	0	0	0	0	0
Max. daily precipitation	6 mm	11 mm	12.2 mm	14 mm	16 mm	16 mm (4/10/75)
<u>Mean Values =</u>						
Air temp.	-1.1°C	-1.7°C	-1.8°C	-1.8°C	1.5°C	-0.2°C
R. H.	62.2%	59.9%	60.4%	61.5%	70.5%	62.9%

Table 5

SNOW SURVEY 1974 - 1975

Snow Depth (cm):

<u>Plot</u>	<u>Dec. 24</u>	<u>Dec. 26</u>	<u>Dec. 28</u>	<u>Jan. 21</u>
A	14.6	10	6	15.7
B ₁	14.6	9.8	4.3	15.2
B ₂	14.6	9.7	3.7	15.5
C ₁	15.2	9.3	1.3	16.8
C ₂	14.6	9.8	0.7	17.2
D ₁	14.3	8.5	0	15.7
D ₂	14	5	0	15.3
E ₁	<u>19.6</u>	<u>13.3</u>	4	<u>18.2</u>
F ₁	16	9.2	4.2	16
F ₂	17.2	9.2	4.3	15.8
<u>Mean Values</u>	15.5	9.4	2.8	16.1

<u>Snow Density:</u>	<u>Dec. 24th</u> (3 measures each)	<u>Dec. 26th</u> (4 measures each)	<u>Jan. 21st</u> (3 measures each)
	B=0.08 g/cm ³	B=0.09 g/cm ³	B=0.16 g/cm ³
	D=0.07 g/cm ³	C=0.11 g/cm ³	
	F=0.04 g/cm ³	D=0.13 g/cm ³	
		E=0.14 g/cm ³	
		F=0.14 g/cm ³	
<u>Mean Values</u>	0.06 g/cm ³	0.12 g/cm ³	0.16 g/cm ³

All values are the means of six observations on each site. Subscripts indicate replicated plots (e.g., B₁).

Figure b

Snow Cover in % of Surface =

becomes involved in soil heaving and needle ice development. Hence, its distribution and redistribution by the wind influences the amount of frost activity seen on the study plots.

In view of measured soil textural conditions (Figures 2 and 4), soil moisture varied predictably across the slope profile. Table 6 summarizes the results of those measurements. The mean soil moisture varied between 25.2% at the surface of site A-B to 47.4% at 10 cm deep in site F. Site D is by far the driest (28.1%) and site F is the wettest (46.7%). In short, sites A, B and C can be considered mesic, site D xeric, and sites E and F are hydric in winter. Those considerations are of great importance to the frost susceptibility of each site.

Relative humidity in the air averaged 62.9%, with a mean maximum of 86.1% and a mean minimum of 39.7% (Table 4). Daily variations are predictably high (Figure 5), with a maximum amplitude on January 20 (95%) when the lowest value of the season was recorded (5%).

Mean air temperature for the period was -0.2°C , with February as the coldest month (monthly mean of -1.8°C). The highest temperature recorded was 19°C on March 20 and the lowest -22.0°C on January 11 and February 5. An average 11.6 hours of each day were above freezing temperatures; the actual number increasing through the period from 8.2 in December to 14.8 in April.

Discontinuous measurements of soil temperature have been maintained through the period and the results of this program are summarized in Table 7. Plot D, at the mid-slope position and facing southeastward, is obviously in the warmest situation, while Plot F (on the valley floor) is slightly colder than Plot B (on the pediment surface). Temperature gradients within the

Table 6

SOIL MOISTURE CONTENT

<u>Site</u>	<u>Depth</u>	<u>Soil Moisture Content</u>	
			<u>Mean</u>
A-B	5 cm	25.2%	
	10 cm	31.1%	33.9%
	20 cm	45.3%	
C	5 cm	27.9%	
	10 cm	35.0%	31.4%
D	5 cm	26.1%	
	10 cm	28.7%	28.1%
	20 cm	29.4%	
E	5 cm	37.0%	
	10 cm	39.3%	40.0%
	20 cm	43.6%	
F	5 cm	46.1%	
	10 cm	47.4%	46.7%
	20 cm	46.5%	

All values are the means of 50 observations.

Table 7

MEAN SOIL TEMPERATURE VALUES

<u>Site</u>	<u>Depth</u>	<u>Mean Temp. in °C</u>	<u>Temp. Gradient from 2-10 cm</u>	<u>Temp. Gradient for Site B</u>
B	2 cm	3.97	0.13 °C/cm	2-5 cm: 0.23°C/cm
	5 cm	3.28		
	10 cm	2.89		5-20 cm: 0.10°C/cm
	20 cm	2.72		
D	2 cm	5.70	0.12°C/cm	
	10 cm	4.76		
F	2 cm	3.20	0.11°C/cm	
	10 cm	2.33		

Values are means of 63 observations.

soil are similar at all three plots and have reached as much as $0.23^{\circ}\text{C cm}^{-1}$ in the upper 5 cm of soil. Continuous recording of soil temperatures will provide more useful information in the future. During much of December and January, the soil on the site was frozen below the surface (Figure 8). This is a potentially important observation since a frozen layer would be an impediment to moisture transfer to the surface for ice segregation there.

Wind speeds have only been observed on the site since March 10 (Figure 9). In the month to mid-April, the mean at 3 m above ground level was 15.9 km hr^{-1} and at 0.5 m height 10.5 km hr^{-1} . No information on gust velocities are available, but Figure 7 shows three periods of high winds on March 18, 22 and April 7. Over 24 hours on April 7, mean speeds of 46.8 km hr^{-1} (at 3 m) and 31.7 km hr^{-1} (0.5 m). This is not a high velocity: on January 20, 1975, a gust velocity of 140 km hr^{-1} was recorded at the Rocky Flats Plant.

A comparison of 1974-1975 and earlier winters on Rocky Flats

The empirical probabilities of frost/wind erosion on Rocky Flats have been estimated on a monthly or semi-monthly basis from earlier weather records (Table 2; Figure 1). A similar analysis has also been performed for the 1974-1975 winter, again using the record from the Rocky Flats Plant. Thus, a comparison with the earlier, longer period is possible which should allow an evaluation of the "normality" of the winter studied.

Figure 10 summarizes the results of this analysis. In 1974-1975, the high wind and precipitation frequencies both follow those of the longer term record reasonably well. The frequency of freeze-thaw cycles does not, however, show the same fluctuations as the longer record. January 1975 experienced an atypically high frequency. Thus, the mid-winter low probability of freeze-

Figure 7(a)

AIR TEMPERATURE

Figure 6

SOIL TEMPERATURES: PLOT B

Figure 1

SOIL TEMPERATURES: PLANT

miles/hour

Figure 5

WIND SPEED

Freezing-Thawing
Cycle.

Freezing-Thawing
Cycle, After
Precipitations.

—— WINTERS 1969-70 , 1970-71 , 1971-72 , 1972-73 , 1973-74 ; (mean).
 ---- WINTER 1974-75 ;

Figure 10

PROBABILITY OF EVENTS:

P_F : Probability of a Freezing / Thawing Cycle.

P_F : Probability of a Freezing / Thawing Cycle Following Precipitations in the past 24h.

Figure 20

PROBABILITY OF EVENTS.

P_c : Probability of winds above 40 mi/hr.

P_d : Probability of Precipitations above .01 inch.

thaw events is not evident in the 1974-1975 record. This has a further influence on the combined probability of freeze-thaw following precipitation which also peaks in late January rather than late February.

This anomaly in the 1975 record should be kept in mind when examining the observed occasions of soil frost development on Rocky Flats. It suggests that January 1975 should have been favorable to frost action (although the influence of higher wind speeds in inhibiting needle ice growth (Outcalt, 1971) and of frozen ground in preventing moisture transport to the surface should be remembered). This is apparently not the normal case (Table 2).

Ice segregation controls during 1974-1975

At the Lindsay Ranch site, moderately cold, calm nights with high relative humidity seem to be conducive to needle ice development, i.e., similar conditions to those required elsewhere (Outcalt, 1971). This is especially true of the interfluvial area of Plots A, B and C, which is the part of the study site on which most needle ice growth has been observed. (Similar soil and topographic conditions occur over a large part of the Rocky Flats area.) One complication has been noted on this site which is due to the effect of snow on the soil surface heat and moisture conditions. This influence is made more complex by snow drifting and so its interaction with the topography.

Detailed observations of ice segregation in the soil commenced on March 1: prior to that date, no needle ice development was observed, although the lack may be a function of the coarse observation interval used. Following March 1, frozen soil characteristics have been described on six occasions (Figure 7), on two of which vertical soil movement (heave and

later settling) was recorded (March 31 and April 4). Two periods after March 1 gave conditions favorable to needle ice growth and ground heave: March 11 - 17, and March 29 - April 4 (Figure 7). During both of these periods, wind speeds were relatively low, mean daily temperatures were below or close to 0°C (with maxima on the days preceding needle ice growth below 0°C) and the relative humidity was continuously high. Precipitation, whether as rain or snow, also precedes each recorded event.

An apparent periodicity of about 15 days length in the temperature record (Figure 7) aids the search for other periods during the winter which show similar conditions. Five such occasions can be identified: December 23 - 29; January 10 - 11; January 22; January 28 - February 4; and February 15 - 22. It seems possible that needle ice growth could have occurred on each of these occasions, although it was not directly observed. Their distribution in time fits reasonably well with the generalized picture of conditions on Rocky Flats shown in Figure 10.

GROUND FREEZING AND THAWING IN 1974-1975

During the 1974-1975 winter, two types of information were obtained on soil responses to freezing and thawing on the Lindsay Ranch site:

1. instrumental records of soil temperature and vertical soil surface movement (heave);
2. visual observations of the soil characteristics following nights of freezing temperatures.

On two occasions, March 31 and April 4, both types of record are available and a total of ten events have been observed and/or recorded (Table 8).

Table 8 CALENDAR OF DOCUMENTED ICE SEGREGATION EVENTS

March 11, 1975: Detailed field observations. Well-developed needle ice.

March 13, 1975: Detailed field observations. Massive frost.

March 14, 1975: Detailed field observations. Well-developed needle ice.

March 17, 1975: General field observation. Massive frost. Continuous temperature recording at B interface.

March 29, 1975: Continuous recording of surface heave and soil temperatures.

March 30, 1975: Continuous recording of surface heave and soil temperatures.

March 31, 1975: Detailed field observation. Well-developed needle ice.
Detail recording of surface heave and soil temperatures.

April 3, 1975: Continuous recording of surface heave and soil temperatures.

April 4, 1975: Detailed field observations. Well-developed needle ice;
continuous heave and soil temperatures recording.

April 14, 1975: Continuous heave and soil temperatures recording.

Figure 14

General Conditions

As previously mentioned, the two periods when consecutive freeze-thaw events occurred are associated with low mean temperatures, precipitation and low winds. Tables 9 and 10 show the general meteorologic conditions for the day preceding each of the ten events that have been described or recorded. A difference can be seen between the six events that were observed on the ground and those that were instrumentally recorded only: the former are more alike than the latter.

During the first of the two frost event periods (March 11 to 17), the mean air temperature (-1.1°C) is warmer than it was during the second period (March 29-April 4) (-6.0°C) and precipitation was also greater (2.2 mm compared to 1.2 mm). Prior to both periods, soil moisture contents increase on all plots but fluctuates widely during the March 11 - 17 period (this may be a function of the timing of observations, but could also reflect vertical water flux during needle ice growth and evaporation following needle ablation when maximum temperatures are relatively high).

Heave Records

A record of vertical soil surface movement is only available from Plot B for the period following March 20 (Photo 3). Figure 23 illustrates the trace from the soil heave recorder (for April 14, 1975).

Hourly values of soil surface heave are summarized in Table 11 and Figure 16. The average amount of surface movement is 5.5 mm with a maximum of 8.7 mm recorded at 0600 hours on April 14. The general form of the heave cycle is similar to that observed by other workers (e.g. Outcalt, 1970, 1971; Fahey, 1973): a progressive, almost linear lifting is followed

Table 9

METEOROLOGICAL CONDITIONS ON THE DAY
PRECEDING SIX OBSERVED FROST EVENTS

<u>Date of Event</u>	<u>Max. Air Temp.</u>	<u>Min. Air Temp.</u>	<u>Max. R.H.</u>	<u>Min. R.H.</u>	<u>Hours Above 0°C</u>	<u>Precipitation for the Two Preceding Days</u>
March 11	-2.2°C	-5.5°C	100%	100%	0	7 mm
March 13	-2.2	-9.0	95	72	0	4
March 14	7.0	-7.0	100	31	12	0
March 17	14.0	-2.0	100	14	18	2.5
March 31	6.0	-11.0	100	28	14	0
April 4	5.5	-7.0	100	45	13	0
<u>Mean Values</u>	4.7°C	-6.9°C	99%	48%	9.5	2.2 mm

Table 10

METEOROLOGICAL CONDITIONS ON THE DAY
PRECEDING SIX RECORDED FROST EVENTS

<u>Date of Event</u>	<u>Max. Air Temp.</u>	<u>Min. Air Temp.</u>	<u>Max. R.H.</u>	<u>Min. R.H.</u>	<u>Hours > 0°C</u>	<u>Precipitation</u>
March 29	-6.0°C	-21.0°C	100%	52%	0	1 mm
March 30	-3.0	-7.0	100	46	0	0
March 31	6.0	-11.0	100	28	14	0
April 3	1.5	-18.0	100	32	1	5
April 4	5.5	-7.0	100	45	13	0
April 14	N.A.	N.A.	N.A.	N.A.	N.A.	0
<u>Mean Values</u>	0.8°C	-12.8°C	100%	40.6%	5.6	1.2 mm

Table 11 HEAVE AMOUNTS FOR SIX RECORDED FROST EVENTS

<u>Date:</u>	<u>Time:</u>									
	<u>1900</u>	<u>2000</u>	<u>2100</u>	<u>2200</u>	<u>2300</u>	<u>2400</u>	<u>0100</u>	<u>0200</u>	<u>0300</u>	<u>0400</u>
March 29								0.5	1	1.8
March 30			1	1.2	1.6	2.1	2.8	3.2	4.4	4.9
March 31						0.8	0.9	1.5	2.1	3.4
April 3		0.5	2	2.8	2.9	3.5	4.1	4.3	4.9	5.3
April 4								1	2.4	3.7
April 14						0.2	2	3.7	5.3	7
<u>Means</u>		0.1	0.5	0.7	0.8	1.1	1.6	2.4	3.3	4.3

	<u>Time:</u>									<u>Max. Heave</u>
	<u>0500</u>	<u>0600</u>	<u>0700</u>	<u>0800</u>	<u>0900</u>	<u>1000</u>	<u>1100</u>	<u>1200</u>	<u>1300</u>	
March 29	2	2.3	2.6	2.5	2.3	1.9	1			2.6
March 30	5.4	6.2	6.8	6.8	6.9	6.4	5	3.5		6.9
March 31	4	5	5.5	2.3	0.4					5.5
April 3	5.7	5.9	6	4	2.3	0.3				6
April 4	4.5	5.1	5.2	3						5.2
April 14	8.5	8.7	5.8							8.7
<u>Means</u>	4.8	5.5	5.3	3.1	2.0	1.4	1.0	0.6		

All values are millimetres of heave above normal ground level.

Figure 16

SURFACE HEAT AMOUNTS (Plot B)

by a much more rapid return to the normal surface level (Figure 23). On average, the rising limb of the heave cycle is 3.3 times as long as the subsequent fall. The period of heaving varies from 16 hours (2100 hours on March 29 to 1200 on March 30) to 7 hours (April 4). Heave initiation varies through 7 hours and termination through 6 hours, but the peak of the cycle (the time of maximum heave) occurred at 0700 hours in 4 of the 6 recorded events.

-- Two heave events (those of March 29 and 30) occurred under a snow cover and may, therefore, be different from the other four recorded.

Temperatures at the soil-air interface on Plot B during the recorded heave cycles are shown in Table 12 and Figure 17. The lowest interface temperature associated with heave is that of -7.3°C on April 3 and the highest, 13.8°C on April 14 (when 5.8 mm of heave were recorded). During the last four heave cycles, the lag between the interface temperature falling below freezing point and the inception of heave is of two hours on March 31, April 3 and 14 and of six hours on April 4. The earlier cycles of March 29 and 30 (when the ground was at least partially snow-covered), are very different. On March 29, the interface temperature remained above 0°C and, on March 30, it did not fall below freezing until 0200 hours when the snow cover disappeared.

Figure 18 summarizes the situation on Plot B with respect to the relationship between the soil surface temperature and ground heave. The interface temperature drops to 0°C at point A and cooling continues to B. Between A and B the amount of heave is inversely proportional to the rate of surface cooling and, even after the surface temperature starts to rise (from B), heave continues to a maximum of 5.5 mm at C (response to subsurface

Table 12

SOIL SURFACE TEMPERATURES DURING SIX
RECORDED FROST EVENTS

<u>Date:</u>	<u>Time:</u>										
	<u>1600</u>	<u>1700</u>	<u>1800</u>	<u>1900</u>	<u>2000</u>	<u>2100</u>	<u>2200</u>	<u>2300</u>	<u>2400</u>	<u>0100</u>	<u>0200</u>
March 29	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.8	0.9	0.9
March 30	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.1	0.0
March 31	4.5	4.5	2.1	1.3	0.5	0.0	0.0	-0.4	-0.8	-1.2	-1.8
April 3	1.2	0.0	-3.4	-5.3	-5.1	-5.0	-3.8	-4.0	-3.7	-6.8	-7.3
April 4	9.0	4.5	1.1	-0.1	-0.2	-0.8	-1.1	-1.1	-1.3	-1.8	-2.7
April 14	20.0	13.0	5.4	1.8	1.0	-0.2	-0.8	-1.0	-1.3	-2.4	-3.0
<u>Mean</u>	5.9	3.8	1.0	0.0	-0.5	-0.8	-0.8	-0.9	-1.0	-2.2	-2.3

	<u>Time:</u>										
	<u>0300</u>	<u>0400</u>	<u>0500</u>	<u>0600</u>	<u>0700</u>	<u>0800</u>	<u>0900</u>	<u>1000</u>	<u>1100</u>	<u>1200</u>	<u>1300</u>
March 29	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.7	0.5	0.5
March 30	0.0	-0.4	-0.6	-0.9	-0.2	0.4	0.5	0.6	8.0	9.5	10.2
March 31	-1.9	-1.7	-2.0	-2.1	4.1	7.0	3.0	7.0	10.1	9.0	7.0
April 3	-7.0	-6.3	-5.8	0.0	5.8	10.5	12.8	16.5	19.0	18.5	18.0
April 4	-1.3	-1.8	-2.9	4.0	7.1	11.0	19.1	21.0	23.4	23.4	22.6
April 14	-4.0	-1.4	-0.4	6.6	13.8	20.0	25*	25*	25*	25*	25*
<u>Mean</u>	-2.2	-1.8	-1.8	1.4	5.3	8.3	10.2	11.8	14.4	14.3	13.9

All values are °C

* 25°C is the upper limit of the recording system.

Figure 17

SURFACE TEMPERATURE DURING HEAVE EVENTS

Figure 18

SURFACE TEMPERATURE AND HEAVE: PLOT B

conditions). The lag between B (the time of minimum surface temperature) and C (the time of greatest heave) is 3.5 hours.

Observed Ice Segregation Events

Table 9 and Figure 19 summarize the meteorological conditions on the days preceding each of the six observed ice segregation events. Only the March 31 event was not preceded by precipitation: the average for the two days before an event was 2.2 mm. Air relative humidity was high in all six cases - the maximum never below 95% and the minimum averaging 48%. Air temperature was variable (4.7°C to -6.9°C) with the March 17 event apparently occurring under abnormally warm conditions.

Soil temperatures, too, are quite variable during needle ice events (Figure 20), but are generally above freezing at 2 cm depth at the times when ice needle growth was observed. Soil moisture conditions vary distinctly between the plots (Figure 21): Plots E and F are very much wetter than Plots A, B, C and D. With such different moisture conditions, a difference in the soil response to freezing may be expected (and was found). Of the upper four plots (all on material derived from the Rocky Flats alluvium), the moisture profile at Plot D is particularly variable, which may reflect its position on the slope or the influence of the underlying contact between the alluvium and the Pierre Shale.

In general, while there is considerable variation in the atmospheric conditions preceding ice segregation events and also in the conditions on different study plots, the state of the soil on the same plot tends to be quite similar at the start of each event. This is illustrated in the description of each event individually which follows.

Figure 19
Some Climatic data For the day Preceding
the observed Soil Frost.

* notes the figures for the precipitations are
Based on the two days preceding the event.

Figure 20
YSI Soil temperatures at the time of the observation -
in degrees Celsius.

Figure 21

Columnar Soil Moisture at the time of the observations (in %)

Event 1 (March 11, 1975)

Preceding Conditions: On March 10, the mean air temperature was -3.75°C , and at 1700 hours, the air was calm under 100% overcast with between 3 cm and 6 cm of melting snow covering the ground to 50% (at Plots A and B) and 90% (on the valley floor).

At 0800 hours on March 11, the time of observation, the air temperature was steady at -0.5°C with no wind and an overcast sky.

Plots A and B (Figure 22a): Upper 2 cm of soil massively frozen with no thaw at the surface. A well-developed layer of clear needles between 5 mm and 12 mm in length underlay the frozen cap. The needles and the cap above them separated easily from the unfrozen, wet soil below them. The microtopography of the unfrozen soil was much smoother than the surface of the frozen cap.

Plot C: Soil surface already unfrozen and wet with a rough (nubbin) surface. Needles are presumed to have thawed before 0800 hours.

Plot D: Wet and unfrozen soil at the surface. In places, mud covered clear needle ice 2 mm to 5 mm long with wet, unfrozen soil under the needles. A rough surface similar to Plot C.

Plot E: A relatively smooth soil surface with interstitial ice frozen in situ and no evidence of ice segregation.

Plot F: Soil frozen in similar manner to Plot E with some "isometric" ice crystals (1 - 2 mm in size).

Event 2 (March 13, 1975)

Preceding Conditions: At 1700 hours on March 12, air temperature was 15°C with no cloud, 15 km visibility and a light breeze from the northwest.

Figure 22

Figure 22

FIGURE D

detail of Needle ice:

FIGURE E

Melting snow covered 60% of Plots A and B, 30% at Plot C and 80% at Plots E and F. There was no snow at Plot D.

At 0715 on March 13, the sky remained clear with infinite visibility, no wind and an air temperature of 7.5°C . The snow cover was reduced to 10% and was frozen. In general, the soil was hard frozen and its surface only slightly rough (5 to 10 mm high).

Plots A, B and C: Solid soil frost with no heave or ice crystals evident — in the soil.

Plot D: Some small "isometric" ice crystals found in an otherwise massively frozen soil; "radicular" ice in small soil cavities and vapor crystals at the base of pebbles.

Plots E and F: Comparable to Plot D, but with a smoother soil surface.

Event 3 (March 14, 1975)

Preceding Conditions: At 1700 hours on March 13, air temperature was 13°C with 70% cloud cover and a slight breeze from the northwest. The soil was wet and unfrozen on Plots A, B, C and D and saturated and unfrozen on Plots E and F.

At 0740 hours on March 14, air temperature was 12°C under clear sky with no wind.

Plots A, B, C and D: An upper frozen soil cap of 15 mm over 10 mm to 15 mm dirty ice needles. Under the latter is 10 mm of frozen soil. Soil surface is very rough (Figure 22e).

Plots E and F: As March 11 (Figure 22b).

Event 4 (March 17, 1975):

Preceding Conditions: Not recorded on March 16.

At 0740 hours on March 17, air temperature was 1.8°C under 100% overcast with slight breeze from the northwest.

Plots A and B: Soil massively frozen to 20 mm depth with a rough surface.

Some vapor crystals under the frozen cap.

Plots C and D: As Plots A and B, but thaw starting at the surface.

Plots E and F: Massive frost with no visible ice segregation. A smooth surface just beginning to thaw.

Event 5 (March 31, 1975)

Preceding Conditions: At 1420 hours on March 30, air temperature was 7.1°C with clear sky and light northwest breeze. The soil was moist to saturated and unfrozen with 30% snow cover on Plots A and B and 80% on Plots E and F (no snow on C and D).

At 0600 on March 31, air temperature was 1.8°C with clear sky and very light breeze from the northwest. Snow cover was reduced to 1% on Plots A and B and 30% on Plots E and F.

Plot A: Massively frozen, similar to March 17 (Event 4).

Plot B: Well-developed needle ice up to 18 mm thick under a 15 mm frozen cap with rough soil surface (Figure 22a).

Plots C and D: A 20 mm to 30 mm soil cap over 9 mm to 12 mm of clear needle ice. Needles absent above pebbles in the soil (Figure 22c).

Plots E and F: Soil massively frozen with no ice segregation.

Event 6 (April 4, 1975)

Preceding Conditions: No record from April 3.

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At 0740 hours on April 4, the air temperature was 7.1°C with a clear sky and a light northwest wind. Snow cover on Plots A and B was 15%, on Plots C and D 50% and E and F 60%.

Plots A, B, C and D: Well-developed clean needle ice under a 20 mm frozen soil cap and a very rough surface. Thawing starting at the surface.

Plots E and F: Soil massively frozen with a smooth surface.

Summary

Despite the indications of soil textural analysis discussed earlier, only massively frozen soil has been observed on the valley-floor plots (E and F) on the Lindsay Ranch site. Plots A, B, C and D, on the other hand, are much more susceptible to ice segregation, usually in the form of clean needle ice under a solidly frozen soil cap. Dirty ice needles have been rarely encountered in the period of detailed observation.

The usual effect of this ice segregation has been to increase the roughness of the soil and to induce heaving of the surface. A reduced density in the surface is implicit in this response, also. The surface effect is retained for several days after each needle ice event (even in relatively high winds) and the ground only becomes smooth again after rain or snow.

With in situ freezing of soil moisture on Plots E and F, there seem to be few long-lasting effects of ground freezing.

CONCLUSION

The preliminary work described here allows at least an initial evaluation of the possible linking of frost action and wind erosion. The historical

record of weather observations for Rocky Flats shows that these two processes coincide in the spring and fall periods each year and that spring, after soil moisture recharge, probably involves the greatest activity of the year. This is also the period when the highest monthly concentrations of airborne radioactivity have been recorded around Rocky Flats.

The significance of the spring period is substantiated by field observations during 1974-1975, although that single year may not have been a truly representative one. Observations show an increase in the frequency of frost events, and the soil surface disturbances which they induce, in March. At that time, two periods of freezing and thawing of the surface soil were observed in some detail. Both are periods of low air temperatures, relatively high atmospheric humidity following precipitation and low wind speeds. The soil responses in these periods are similar to those described in the literature and are best expressed on the flat pediment surface at the top of the Lindsay Ranch site.

It should be acknowledged that the period of increased frost activity found in March 1975 corresponds to an upgrading of the observational procedure on the study site, by which it may be explained. It is now necessary to extend this record with the same level of precision (or better) through an entire winter from October to May. In this extension, major improvements are planned in the recording of wind data and in the visual observation of soil characteristics. Other improvements in the measurement of soil temperatures and ground heave are also planned for the 1975-1976 winter.

In the remainder of the present budget year (to September, 1975), the field work for the mapping of soil frost susceptibility on Rocky Flats will be completed. This involves soil sampling in a variety of topographic

situations from the surface (0 - 2 cm) layer, which is affected directly by frost and wind, and from the 5 - 10 cm deep layer, which presumably supplies or transmits the water for frost heave and needle ice growth. The application of a topographic - snow drift model to the field area, to allow the identification of areas of greatest potential wind erosion, is also planned for the summer of 1975. Progress along these lines will be reported later.

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APPENDIX I

Field Instrumentation

A. The following instrumentation has been purchased on this contract (to June 1, 1975).

- 1 Data acquisition system (sensor-recorder interface)
 - with 3 fixed range temperature channels (-25° to 25°C)
 - 1 automatic expanded range temperature channel (-25° to 25°C with 5x expansion in the -6.25° to 6.25° range)
 - 2 wind speed channels
 - 1 wind direction channels
 - 1 vertical motion channel (for ground surface heave)

The system has capability for digital recording
(not in use) \$5,000

1	Digital precision voltmeter	300
	Miscellaneous meteorological instruments (thermometers, psychrometer, etc.)	200
1	Instrument shelter (standard Weather Bureau)	300
1	Chest Freezer	250
	Miscellaneous tools	200
		<u>\$6,250</u>

B. The following equipment belonging to the University of Colorado, Institute of Arctic and Alpine Research, is in use on this contract.

- 1 Y.S.I. thermistor bridge and a variety of thermistors
- 1 Soil Test soil moisture bridge and resistance blocks
- 1 Hygrothermograph
- 1 Rustrak temperature recording system (no longer in use)
- 4 Esterline Angus strip chart recorders
- 2 Totalizing anemometers and mast
- 1 Recording precipitation gauge (weighing bucket type)
- 1 Barnes PRT-10 radiation thermometer
- 1 Light trailer for personnel and recorder shelter
- Laboratory equipment for soil texture and moisture analysis

Soil Temperature - Soil Cells

APPENDIX II

APPENDIX III

Location Map and Photographs

PLOTS LOCATION AT THE LINDSAY FARM SITE .

Photograph 1.

The Lindsay Ranch Site, late Spring

1975. Study plots A through F are shown and the instrument shelter (WS) and rain gauge (RG).

Photograph 2.

A low-level air oblique of the

Lindsay Ranch Site, mid-March 1975. This shows a common pattern of snow distribution with no cover on Plot D because of radiation melting. Note, also, the scour pattern downwind of the personnel trailer.

Photographs 3 and 4.

Needle ice from the vicinity of

Plot C, Lindsay Ranch Site, mid-March 1975. In addition to the vertical columnar structure of the needles, horizontal banding of dirty and clean ice can be seen. Scale in centimeters.