MASTER

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

Final Report

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September 1978

Prepared For

THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. EY-76-S-02-2517

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ACKNOWLEDGMENTS

The work reported here has benefited from the advice and assistance of a number of people, mainly in the Institute of Arctic & Alpine Research, University of Colorado and the Department of Energy. In particular, thanks are due the project monitors, Dr W.S. Osburn, who first suggested that frost action might contribute to resuspension from contaminated soil at Rocky Flats, and Dr W.T. Hinds. The project was also greatly assisted by the advice of Dr S.I. Outcalt, University of Michigan and Dr C.B. Jenner, University of Wisconsin, both of whom acted as external commentators during the early years of the work. The development and maintenance of field instrumentation has been largely due to the expertise of John Clark and Chet Welles at the University of Colorado. Important technical assistance in the form of soils analysis has been given by Rolf Kihl, INSTAAR Sedimentology Laboratory. In the field, the main part of the observational program has been conducted by Pierre Morin, ably assisted by Clifton Mitchell. During the last year of observations, this work was continued by John Dixon and Bill McCoy. The last four individuals have also contributed greatly by reducing large volumes of field-derived data, a job in which the assistance of Margaret Eccles has proven most important.

ABSTRACT

This study of the potential links between soil freezing and wind erosion has been conducted at Rocky Flats during 4 winters. Most of the study has involved the conditions leading to the growth of segregation ice in the surface soil and the ground heave which that produces. This occurs about 15 times in the average winter at Rocky Flats, always on a diurnal cycle. Such frost action is preferentially distributed in time and space and cannot be estimated from air temperatures alone. November and March are the months of most frequent frost heave, and then only in the days following precipitation or snowmelt. The most marked frost effects are found on exposed interfluvial and hillcrest situations, where there are patches of bare soil. Almost no effects are found on the valley floors.

Soil disturbance by segregation ice leads to a marked decrease in soil bulk density, and presumably in soil strength though this change has not been quantitatively defined. However, this does not lead to wind erosion of the soil at the study site because that surface is more influenced by the vegetation cover than by the soil characteristics.

INTRODUCTION

This study was undertaken to investigate the possibility that frost action in the soils of Rocky Flats might facilitate their later erosion by the wind. Such a relationship could then provide a mechanism whereby the resuspension of contaminated soil could be effected and was, in fact, first postulated on the evidence of apparently seasonal variations in Pu concentrations in the ambient air at Rocky Flats. These concentrations tended to peak in Fall and Spring (Dow Chemical Co. 1973, 1974, 1975), when most frequent frost cycles might be expected.

This is the final report of the study of soil frost in the Rocky Flats area. It is based upon empirical observations and surveys made during the winters of 1974-75 to 1976-77 which have been summarized in three earlier progress reports (Caine et al. 1975, 1976, 1977).

THE PROBLEM

The general hypothesis which this project was intended to approach was initially outlined in the manner of Figure 1. This suggests that frost action in the surface soil leads to a temporary decrease in its bulk density and mechanical strength and an increase in its surface roughness. All of these changes should, in turn, contribute to an increased probability of soil erosion by the wind, other things being equal, and so movement into the air of any contaminants in the surface soil.

Such a general statement is not easily evaluated, except in similarly general terms, and so further definition and the imposition of constraints on the field of study became necessary at the start of the project. Some of the more important of these constraints are included here as part of a problem definition:

Figure 1

HYPOTHESIZED PROCESS - RESPONSE LINKS

SOIL INFLUENCES

CLIMATIC INFLUENCES

- a) The model of Figure 1 is for surface effects and so no more than a shallow surface layer of soil need be considered. Deeper soil materials, and soil freezing, are only important in so far as they influence surface responses. The most marked surface effects are probably produced by diurnal freeze-thaw cycles and decay of needle ice (French 1976, p. 33) in the soil. The effects of needle ice are exemplified by Figure 2 and have received most emphasis in this study.
- b) Disturbing influences other than those due to frost should be minimized and so the study was of "natural" conditions in the Rocky Flats area. The conclusions drawn from it are, therefore, only directly applicable to those and similar conditions. In particular, they do not apply to situations in which artificial disturbances, as by traffic, occur.
- c) Since this was largely an empirical study, its results are influenced by the time period and area in which it was conducted. The extrapolation of empirically-derived results requires care and may be subject to wide errors, even when they are physically meaningful.

In evaluating the effectiveness of frost action in preparing the soil for wind erosion, three jobs form the basis of this report. They involve different scale considerations and have received different emphasis in the study. In order of appearance in this report, they are:

- a) An evaluation on a broad spatial scale, involving most of the areas of Rocky Flats and leading to a general estimate of the variability of frost action in that area. From this, a general map of frost susceptibility in the Rocky Flats soils is derived.
- b) Temporal studies to define the frequency and magnitude of frost and wind activity, both during the period of study and in an earlier period (using any available records for the latter).
- c) Site studies which combine these two in detail on a single "representative" site. It is probably only at this level that the links shown in Figure 1 can be adequately evaluated and, even then, not all of them have been approached directly and consistently in this study.

Figure 2

NEEDLE ICE AND ITS EFFECTS ON THE SOIL

The upper photo shows needle ice in the soil at Rocky Flats (scale in cm). The lower photo is of the soil surface after ice needle ablation and shows a much roughened surface.

THE STUDY AREA

The topography of Rocky Flats (Figure 3) provides a useful framework for describing the environment of the area since it corresponds closely to variations in geologic materials, soils, vegetation and surface hydrology. In this report, therefore, reference is often made to topographic position, especially to a three-way breakdown according to Interfluvial, Valley-side or Valley-floor situation. These three situations are illustrated by a cross section of the valley of Rock Creek at the Lindsay Ranch (Figure 4). This includes the site on which detailed observations were made during the study.

The highest parts of the Rocky Flats scenery consist of the remnants of a dissected pediment which slopes at low gradient (1° to $1\frac{1}{2}^{\circ}$) to the east and northeast, away from the mouth of Coal Creek Canyon (Figure 3). The interfluvial between the valleys reflect this old surface and form a series of flat-crested ridges of similar elevation. The pediment truncates Cretaceous bedrock which is usually only exposed in the valleys; the pediment remnants are mantled by a coarse, quartz gravel (the Rocky Flats Alluvium) which may be up to 35 m thick (Ackerman 1974; Hurr 1976). This alluvium is particularly important in the present study because it forms the parent material of the Nederland Series of soils (Moreland & Moreland 1975) which occupy the most exposed sites at Rocky Flats and because it carries a dry prairie vegetation which offers only incomplete protection of the soil surface (Clark & Webber 1975).

The valleys which incise the Rocky Flats pediment by up to 100 m are eroded into Cretaceous sandstones and shales which underlie the Rocky Flats Alluvium unconformably. The larger valleys, e.g. along the lower sections of Rock Creek and Woman Creek, contain alluvial gravels and terraces of late Pleistocene and Holocene age on their floors. Upstream and on the valley walls, clay loam soils are developed from the sandstones and shales of the Laramie and Arapahoe Formations and these carry a moist vegetation which offers a better ground cover, though one that is variable with orientation and exposure. Landsliding is evident on a number of these valley walls where slope gradients are steep and mass wasting on the upper parts of the slopes has transported a mantle of Rocky Flats Alluvium downslope. The lower edge of this transported mantle is frequently marked by springs and seepages, with the accompanying change to a wet vegetation of scrub cover similar to that found along the stream channels at the valley centers.

Figure 3

LOCATION MAP

FIGURE 4

THE LINDSAY RANCH SITE

KEY: Vegetation 3 - Dry Communities, 4 - Wet Scrub, 6 - Moist Meadow, 7 - Streambank, 8 - Wet Marsh Vegt.
Geology Qrf - Rocky Flats Alluvium, Early Pleistocene; Klu - Upper Laramie Formn., Cretaceous.

The correspondence of bedrock, topography, soils and vegetation in the Rocky Flats area is well illustrated by work of Moreland & Moreland (1975); Clark & Webber (1975) and Hurr (1976). Here, it is sufficient to define it by a table of 2 values for the characteristics of the sites used in the empirical study of frost action described later in this report (Table 1.). This shows a high level of association between all four of these environmental characteristics.

Table 1

ASSOCIATION AMONG SITE CHARACTERISTICS

	Topography	Geology	Soils	Vegetation
Topo.	_____	29.2	22.1	39.5
Geol.	6	_____	37.0	21.4
Soils	4	6	_____	13.5
Vegt.	4	6	4	_____

Upper half of table consists of 2 values, the lower half, the corresponding degrees of freedom.

All values are significant with $p < 0.01$.

FROST ACTIVITY ON ROCKY FLATS

Apart from freezing temperatures, two other environmental characteristics are important in defining spatial variations in frost activity; the nature of the soil and the availability of moisture. These two interact in the production of needle ice which grows best when the upward transport of water to the freezing front is sufficient to prevent further downward movement of the 0°C isotherm in the soil (Outcalt 1971). In this process, soil characteristics control rates of water movement at a given suction while the amount of available moisture limits the volume of segregation ice produced.

Both soil texture and moisture vary spatially on Rocky Flats: the former with the soil and its substrate, the latter with the soil texture, the depth to groundwater and the nature of the precipitation. In winter and spring, an important modification to the latter imposed by the effects of wind drifting which concentrates the snow cover in some places while removing it from others. Snow drifting is also significant in this study as a surrogate for eolian soil erosion: the areas from which the snow cover is removed will probably be those which are most open to wind erosion of the soil.

In this part of the report, three lines of evidence drawn from a large part of Rocky Flats are considered:

- a) Soil frost susceptibility, treated indirectly on the basis of soil and drainage conditions;
- b) Frost disturbance of the soil surface, evaluated by empirical field survey;
- c) Snow cover following episodes of wind drifting.

The first two of these lead to a general view of the controls of frost action in this environment which allows mapping of frost susceptibility in the surface soils of the area. The last allows a modification of this to take into account very local sources of moisture and also defines the areas most prone to wind erosion.

SOIL FROST SUSCEPTIBILITY

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). In addition, 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, early emphasis was 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

The thickness of the soil affected by individual needle ice events and the depth from which water is drawn to the base of growing needles must vary considerably with weather and soil conditions. However, it has not been possible to include these considerations when sampling to define soil characteristics in a general way and so samples were taken from the same two levels in each of the soil profiles examined; 0 - 2 cm and 10 - 15 cm depth. The rationale for this is that the uppermost sample would represent the soil disturbed by needle ice growth while the sample from lower in the profile should be characteristic of the soil from or through which water is drawn during ice segregation. Because different processes are involved at the two depths, the analysis of the two samples from a single profile has rather different requirements.

Spatially, sampling was stratified according to topography since other surveys (e.g. "The Field Area": above) suggest relatively simple relationships among the environmental characteristics of the Rocky Flats area which can then be keyed to topography. Three basic topographic situations are used in this study:

- a) The interfluvial situations on the Rocky Flats pediment;
- b) The upper parts of the valley sides where the Rocky Flats Alluvium has a steeper gradient and more variable aspect than on the pediment itself;
- c) The lower valley sides and valley floors which are underlain by Cretaceous bedrock with, perhaps, late Pleistocene and Holocene alluvium on the lowest parts.

Soil Texture

The results of sampling for soil textures in the Rocky Flats area are summarized in Figures 5, 6, 7, and 8. 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 depth below the ground surface, there are no major textural differences between the fine fractions of soils on the interfluvial areas 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 7 and 8). Since the valley side sediments have been derived from the rocky Flats Alluvium of the interfluvial areas, 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).

Spatially, the main difference in soil textures occurs between the interfluvial and valley-side materials and those of the valley floors, i.e. between the soils on the Rocky Flats Alluvium and those on the underlying Cretaceous bedrock (Figures 5, 6, 7, and 8). However the data are presented, this contrast is evident. Two types of material are found on the lower valley sides and floors, both of them clearly differentiated from the Rocky Flats Alluvium. Close to the stream channels is a sandy material which probably represents late Pleistocene and Holocene alluviation by fluvial processes. On the lower slopes of the broad valleys is the finer material of caly-loam soils which seems to have been derived, approximately in situ from the underlying Arapahoe and Laramie Formations.

Frost Susceptibility

Initially, the frost susceptibility criteria of Beskow (1935) were used in evaluating the surface materials at Rocky Flats (e.g. Figure 9). Unfortunately,

Figure 5 TEXTURE TRIANGLE: PARTICLES SMALLER THAN 2MM
(0 - 2 cm depth)

Figure 6 TEXTURE TRIANGLE: PARTICLES SMALLER THAN 2MM
(10 - 15 cm depth)

Isopleths are approximate permeabilities (g/day/ft²)

Figure 7 TEXTURE TRIANGLE: BULK SAMPLES (0 - 2 cm depth)

Figure 8 TEXTURE TRIANGLE: BULK SAMPLES (10 - 15 cm depth)

Table 2

SURFACE / SUB-SURFACE DIFFERENCE IN CLAY CONTENT

Situation	N	$\bar{x}$		
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 $H_0 : x = 0.0$. The means are for the differences (clay % at 0.2cm depth) - (clay % 10-15 cm depth).

almost all of the materials sampled fall within the envelope of susceptibility which then fails to provide a dichotomous classification of them. However, because the cumulative grain size curves are approximately parallel, a simple surrogate which provides an estimate of relative susceptibility is provided by the sand (2000 - 63μ) content of the soil. This should be inversely related to frost susceptibility as defined in early work (Beskow 1935).

However, the real relationship between needle ice growth and the sand fraction of the surface soil is not well defined. It is probably non-linear and variable with the other fine fractions of the soil and their mineralogy. For the present, we suggest a form like that shown in Figure 10 which represents an unscaled product of the variabilities of hydraulic conductivity and soil suction with sand content.

In considering the sand content of the less-than 2 mm fraction of the surface soil, three situations on Rocky Flats (again related to topography) are shown to be statistically different (Table 3). These are:

- a) The interfluvial and upper valley-side areas; i.e., where the soils are derived from the Rocky Flats Alluvium.
- b) The clay loam soils of the valley floors, derived from Cretaceous sandstones and shales.
- c) The valley floor deposits of late Pleistocene and Holocene alluvium.

The second of these may be expected to vary with the lithology of the parent material but we have not been able to define that difference.

This classification, in combination with Figure 10, suggests that the most susceptible materials to needle ice segregation are those found on the influvial areas and upper valley sides. These materials cover large parts of the Rocky Flats area and are also found in the situations where the vegetation cover is least complete and the soil most exposed to wind action.

In addition to soil texture, the mineralogy of the soil fines (especially the clay fraction) is known to influence frost heave (Lambe et al. 1969). Kaolinite minerals, and particularly halloysite, tend to intensify heave amounts whereas sodium-montmorillonite tends to inhibit it. These influences have not been studied in detail in this project because a preliminary study of the clay mineralogy of the surface soil at the

Figure 9 SURFACE SOIL TEXTURE: LINDSAY RANCH SITE

The solid line is the approximate boundary between susceptible and non-susceptible soils (after Beskow).

Lindsay Ranch site showed little spatial variability. The dominant species present are illite/hydrous mica, kaolinite and quartz and these are evident in approximately the same proportions in the X-ray diffractograms of samples from all topographic situations on this site. In view of this lack of variability, no further work has been done on this topic; the effects of clay mineralogy do not seem sufficient to account for spatial variations in the observed amounts of needle ice activity at Rocky Flats.

Water Relationships

The preliminary work of Hurr (1776) shows that the ground water table in the Rocky Flats Alluvium rarely rises to within 50 cm of the ground surface, and then only for brief periods. In light of this, and the fact that needle ice growth and ablation tends to be a diurnal phenomenon requiring a water source close to the ground surface, the influence of ground water is neglected here. While this assumption may be reasonable for the interfluvial and upper valley side situations, it is less satisfactory if applied to the valley floor situations on Rocky Flats. There, the water table is much closer to the ground surface and needle ice growth is common along the stream channels.

As an estimator of the reservoir from which water for ice segregation is drawn, the characteristics of the soil at 10 - 15 cm depth is used here. 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 (Figure 11) 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 12; Table 5)

Analysis of variance of the available water estimates for the 10 - 15 cm. depth sediments shows a significant ($p = 0.05$) difference between the three topographic situations included in the analysis (Table 4). The

Table 3

SURFACE SOILS: SAND CONTENT

<u>Situation</u>	<u>N</u>	<u>$\bar{x}$</u>		
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

<u>Source</u>	<u>S.S</u>	<u>d.f</u>	<u>M.S.</u>	<u>F</u>
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.

Figure 10

FROST SUSCEPTIBILITY AND SAND CONTENT

K - Permeability

M - Moisture content, equivalent soil suction

FS - Frost Susceptibility

Figure 11 SOIL MOISTURE TENSION CURVES

Letters (A through F) refer to samples from the plots on the Lindsay Ranch study site.

Figure 12

AVAILABLE WATER AND SAND CONTENT

Table 4

SUB-SURFACE SOILS: AVAILABLE WATER

Situation	N	$\bar{x}$	s^2	s
Interfluvial	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

Source	S.S.	d.f.	M.S.	F
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 suctions.

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

Table 5

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

differences between interfluves, valley-sides and the valley-floor alluvial fills seems to be a real one. (The clay-loam soils derived from the Cretaceous sandstones and shales could not be included in the analysis because of an inhomogeneous variance estimate.)

Discussion

This analysis shows a clear difference in terms of soil texture and moisture relationships among the environments found at Rocky Flats. This variability follows the pattern found in the geology and vegetation of the area and, when added to the effects of topographic exposure, suggests wide differences in frost susceptibility. In fact, the differences in soil texture and drainage are so great as to suggest that they should override the effect of other influences on frost activity and be sufficient to allow definition of zones of different frost susceptibility.

On the indirect evidence, therefore, we might suggest three levels of frost susceptibility, and the soil materials allocated to them, as:

- a) Most susceptible is the Rocky Flats Alluvium of the interfluvial areas and upper valley sides;
- b) Least susceptible are the clay loams of the lower valley sides and valley floors;
- c) Subject to very variable local influences (predominantly due to water levels) are the sandy materials of the late Pleistocene and Holocene alluviums.

This classification can then be used as a hypothesis and tested empirically by field surveys of the evidence of soil frost activity. Such a test includes more than just the nature of the material, since it involves local climatic conditions also, but is nevertheless a reasonable way to proceed.

FIELD SURVEY OF FROST ACTIVITY

An empirical test of this evaluation was made during the latter part of the 1976-1977 winter. At that time, repeated field surveys were made on a wide scale at Rocky Flats as a search for surface soil disturbance by needle ice. The results of this and the indirect evidence of soil textural studies

then became the basis for mapping of soil frost susceptibility around the Rocky Flats plant.

Field observations were made at marked stations on four transects, one at each corner of the inner buffer zone at the Rocky Flats plant site. Each transect was located qualitatively so as to intersect a cross section of the environments of the buffer zone and was surveyed on the ground on a weekly (or shorter) interval during the last three winter months of 1976-1977. The lack of a record for the period prior to January 1977 is probably not serious, since the record from the Lindsay Ranch shows little frost action in the early part of the 1976-1977 winter (below). The use of a short interval between successive surveys makes statistical evaluation difficult because the soil surface has a memory of more than a week and so the data from different surveys are not independent. This problem is avoided here by treating surveys separately and not pooling results from different surveys.

At each station, the area within 5 m of the station was examined for evidence of soil disturbance by frost heave and a four-part scale used to describe the observed condition of the soil surface. These observations were made by the same observer on all occasions and were based upon criteria requiring visible effects at the soil surface (Table 6; Figure 2). The absence of such visible evidence does not mean per se the absence of soil freezing but it is reasonable to suggest that frost disturbance contributes little to eolian erosion.

Results

The data summaries included here (Table 7) show a pattern which supports the inferences made from soil textural studies earlier. These tests have been conducted explicitly in terms of topographic position but the high level of correspondence between topography and other environmental factors at Rocky Flats should be remembered (Table 1 is derived from the characteristics of the sites used in this survey). Implicitly, the χ^2 analyses of Table 7 include the effects of geology, soils and vegetation as well as topography. In terms of topography, however, it is clear that most evidence of frost action is found on the interfluvial areas that, with distance downslope, the effects of frost become increasingly less evident.

Table 6

SCALE OF FROST EVIDENCE ON SOIL:

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

Table 7

FROST DISTURBANCE BY TOPOGRAPHY

March 8 1977

	Frost Disturbance				
	0	1	2	3	
Interfluve	1	1	0	12	$\chi^2 = 24.8$
Slope	11	5	10	3	d.f. = 6
Valley	2	0	1	3	

March 17 1977

	Frost Disturbance				
	0	1	2	3	
Interfluve	1	0	2	12	$\chi^2 = 23.3$
Slope	8	5	11	5	d.f. = 6
Valley	3	0	0	1	

April 7 1977

	Frost Disturbance				
	0	1	2	3	
Interfluve	1	1	4	9	$\chi^2 = 14.3$
Slope	9	8	4	8	d.f. = 6
Valley	4	0	0	2	

Note: Too few creek bank stations were included in the surveys for inclusion in this analysis.

Table 8 FROST DISTURBANCE BY LITHOLOGY: MARCH 8, 1977

	Frost Disturbance			
	0	1	2	3
Valley Fill	4	0	0	1
Rocky Flat Fill	1	2	4	14
Arapahoe Formn	5	3	5	2
Laramine Formn	2	1	2	2

Table 9 FROST DISTURBANCE BY SOIL TYPE: MARCH 8, 1977

	Frost Disturbance			
	0	1	2	3
Clay Loams	7	1	7	5
Nederland Series	3	3	4	14
Argiuststolls	3	2	0	0

Table 10 FROST DISTURBANCE BY VEGETATION: MARCH 8, 1977

	0	1	2	3
Dry Vegt.	4	2	3	13
Meadow(moist)	6	4	6	3
Scrub	0	0	2	2
Wet (swamp	4	0	0	0

Despite the interdependence of local environments on Rocky Flats, it is possible to make some general comments about their influence on frost action. This should assist in allowing extrapolation from survey sites and in mapping.

Topography. Table 7 shows a good correspondence between the three topographic situations defined earlier and the field evidence of soil disturbance by needle ice. The interfluvies of Rocky Flats are the preferred zones for frost action, the valley floors are areas of little frost activity, and the valley sides show intermediate susceptibility to frost. An important exception to this generalization occurs along the creeks draining Rocky Flats. On the stream banks, needle ice growth is common in most winters, reflecting the moisture source and a bare soil surface. While this could be significant in bank erosion, it is probably not important in wind erosion because of its protected situation and limited area extent.

Lithology. A clear correspondence is also evident between the frequency of observations of frost action and the lithological environment of each station (following Hurr 1976). Most evidence of frost influences is found on the Rocky Flats Alluvium with apparently less activity on the Cretaceous materials (shales and sandstones) of the Arapahoe and Laramie Formations (Table 8). This influence is one that is obviously confounded with topographic position in that the interfluvie areas are also the situations underlain by the Rocky Flats Alluvium.

Soils. The soils mapped by Illsley & Amen (1974) have been grouped into three categories for purposes of this analysis (a number of other categories could be defined but are spatially unimportant). Deep, well-drained gravelly soils (Nederland sandy loam and Valmont clay loam) correspond to situations of most frost activity (Table 9) but also correspond to topographically high situations underlain by the Rocky Flats Alluvium. The deep clay loams and the more poorly drained calyxes and loams of the valley sides and floors, in contrast, show less evidence of frost influence. A fourth soil type (not shown in Table 9 because few observation stations were located on it) includes the well-drained alluvial soils along the creeks at Rocky Flats. These show

wide variability in their intensity of response to frost action, probably as a reflection of drainage conditions and moisture availability at the time of freezing.

Vegetation. A preliminary analysis of the frequency of observed frost influences under different vegetation units (as mapped by Clark & Webber 1975) matches the distribution pattern defined by other environmental characteristics (Table 10). The variety of dry vegetative units that are characteristic of the interfluvial situations on Rocky Flats correspond to a high level of frost activity while the moist communities on the transects show a greater level of variability in the recorded response to frost action. The wet environments along stream channels and in marsh areas are represented by only three stations and so are not included in Table 7. All three of these stations failed to yield any visible evidence of surface changes due to soil freezing.

Discussion

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

The correspondence of soil characteristics and the field evidence of needle ice activity leads to a relatively simple map of soil frost susceptibility which matches the topography of the Rocky Flats area quite closely. For Zone A (the inner buffer zone around the Rocky Flats Plant) this is presented in Figure 13 which uses three categories of frost susceptibility.

Figure 13

SOIL FROST SUSCEPTIBILITY AROUND
THE ROCKY FLATS PLANT

Snow Cover Variations

Although snow drift sites are shown on Figure 13, these have not been mapped precisely. Instead they have been defined indirectly from site conditions and on the basis of reconnaissance from the air and ground. As in other environments, the location of snow drifts on Rocky Flats fits a simple pattern which recurs in time. Unlike other situations, however, this pattern does not seem to be reflected in the vegetation cover and so cannot be estimated on air photography taken when there is no snow on the ground. Further, the drift size is usually small because the volume of snow in contributing areas upwind is not great. Nevertheless, drifts of 1 m depth (20 - 30 cm water equivalent) are not uncommon and would make a significant contribution to local soil moisture budgets.

The location of these snow drifts is well predicted by the empirical models of other workers, if drifting is assumed to be a response to winds from the west or northwest. They form in situations where a relatively sharp change of slope by more than 17% (ca. $9\frac{1}{2}^{\circ}$) occurs along the air flow lines (Finney 1939; Tabler 1975; Berg & Caine 1975). Snow accumulation in drifts on Rocky Flats is generally constrained by the volume of snow available in the contributing area upwind and so the shape of the drifts rarely approaches an "equilibrium form" (Tabler 1975). Instead, they have a wedge shape in cross-section and are confined to a narrow zone (about 10 m wide) immediately downwind of the topographic break which produces them. They are, therefore, restricted to the soils derived from the Rocky Flats Alluvium and so tend to coincide with the materials thought to be most susceptible to frost activity on Rocky Flats. Because of the added capacity for water storage, these situations should be even more open to frost activity than the other parts of the Rocky Flats Alluvium, but this has not been corroborated by field survey. The lack of corroboration is probably due to the limited area of snow drift development in these zones (Figure 14).

In terms of the general hypothesis tested by this study, this evaluation proves inconclusive. Sites on which snow drifts develop preferentially should be more prone to frost action but, because of their sheltered situation, less prone to wind erosion of the soil. No adequate test of this supposition has yet been performed but the evidence of the snow cover itself suggests its inherent reasonableness, at least with respect to winds from the west and northwest.

Figure 14

SNOW DRIFT DISTRIBUTION ON THE LINDSAY RANCH SITE
AND IN THE ROCKY FLATS AREA.

HISTORICAL RECORDS

The potential for frost action on Rocky Flats has been evaluated by different procedures for two time periods: 1969-1974 and 1974-1978. For the first of these, weather records from the Rocky Flats Plant have been used and, for the second, the records generated by this study on the study site at the Lindsay Ranch. The second set is clearly the more useful one for these purposes and is treated as part of the site studies in the next section. Further, the period prior to 1969 has not been evaluated at all because of the lack of suitable observations from Rocky Flats.

1969-1974: ROCKY FLATS PLANT

Early in the study, a simple probability analysis of data from the Rocky Flats Plant was performed as an initial test of the hypothesis on which this study was based. It provided a frequency analysis of freezing temperatures and high winds in the general area of Rocky Flats which tended to support the model of the present study (Caine & Morin 1975).

Based on the daily time series, we can define for any meteorological event (i) an empirical probability:

$$P_i = n_i/N \quad (1)$$

where n_i is the number of days on which the event was recorded and N is the total number of days in the record. Thus, the probability of a frost in April is defined by number of days with freezing temperatures and the total number of days in the record for April (combining all available years). In this, the lack of stationarity in the time series is ignored and, when it is extended to conditional probabilities, the correlation between time series of different events is also neglected. These are important assumptions.

The six years of record have analyzed for three events:

- a) Freeze-thaw events, each defined as a complete cycle of above-below-above freezing temperatures;
- b) Daily precipitation in excess of 0.01 in;
- c) Wind speeds in excess of 40 mph (18 m sec^{-1}).

The first two of these have also been combined as 'freeze-thaw events immediately following precipitation' (i.e. within 24 hours). The last was initially defined for convenience since the 40 mph threshold is used in the monthly weather summaries from Rocky Flats. It does, however, fit reasonably well to the critical wind speed defined later for the Lindsay Ranch site.

The results are summarized in Table 11 on a monthly and semi-monthly basis and as a smoothed curve in Figure 15. They show the bimodal pattern suggested at the outset of the inquiry, although the bimodality is not so evident as that found in records of frost events at higher elevations in Colorado (e.g. Fahey 1973). The mid-winter period is one of relatively little frost activity, presumably because the air temperature remains below freezing for days at a time. The greatest potential for frost action seems to occur on either side of this period. When this is combined with the precipitation and wind effects (columns (3) and (4) in Table 11), the results 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. This test, based on air temperatures and time periods of two weeks length, is not a satisfactory one for a hypothesis which states ground level effects and response times of hours. For this reason, it was not given further attention after instrumentation of the Lindsay Ranch site.

Table 11 EMPIRICAL PROBABILITIES OF FROST-WIND ACTION: ROCKY FLATS

Month*	(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
Sep 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	0.00	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 15

MEAN MONTHLY WEATHER RECORDS:
ROCKY FLATS PLANT

SITE STUDIES 1974-1978

Detailed records of frost and wind action have been maintained on Rocky Flats during 3 consecutive winters (1974-1977), with some of them being continued through the 1977-1978 winter. This section involves an evaluation of those weather and soil records in terms of the potential for soil erosion by wind and frost. It proceeds from a general consideration of the study site and period to an evaluation of the conditions under which soil disturbance by frost occurs and a discussion of the potential for wind erosion following that.

In all cases, the frost action recorded on Rocky Flats has been of a diurnal nature, i.e. with a period of 24 hours. On the interfluvial areas similar to that on which observations were made, this appears to be generally the case; valley situations occasionally experience longer periods of soil frost which penetrate deeper below the surface. Each diurnal cycle of frost action usually involves vertical lifting of the soil surface during the late-evening and nighttime hours, as freezing occurs, followed by settling during the early day-light hours as thawing is accomplished. For convenience, each event is defined in this report by the date of the evening on which it commenced. In a few cases, frost heave was not initiated until the early morning hours but these are still identified by the date of the previous evening so as to avoid the possibility of two events with the same identifying date. In the 4 winters of record, no heave events with a period longer than 24 hrs have been identified, although it is common for the settling during thawing of the soil to be less than the amount of heave preceding it. This "residual heave" remains when the entire soil mass has a temperature above freezing and thawing is complete. It presumably represents a change in the surface soil density produced by the effects of freezing.

The vertical motion of the soil surface appears to have been produced in most cases by "needle ice" in the uppermost centimeter of soil (French 1976, p. 33) (Figure 2a). In some cases, especially where the amounts of heave involved are slight, it is possible that other forms of soil ice are involved

(the need to maintain an undisturbed surface at the recording site precluded verification of this directly). However, with a limited depth of freezing whenever heave occurs, it must require water movement toward the freezing front and the growth of segregation ice (of which needle ice is one form). This is also suggested indirectly by the control which available water places upon heave occurrence in this study.

The changed potential for wind erosion hypothesized at the start of this project follows from the change in the soil surface which the growth and decay of needle ice induces (Figure 2b). This is only evaluated in terms of potential here, because qualitative observations suggested little contemporary soil movement by wind at the study site on Rocky Flats. The potential for wind erosion is, therefore, estimated from wind records, rather than from observed erosion.

THE STUDY SITE

The study has been concentrated at a site just west of the Lindsay Ranch, about 1 km northwest of the Rocky Flats Plant. This site lies on the north side of the valley of Rock Creek and runs upslope from the stream channel across the valley side to the pediment surface of the interfluvium. Most work has been done at the top of the site, in the interfluvium situation, where patches of exposed soil suggest the greatest potential for frost disturbance of the surface material. This supposition is supported by empirical work on the site, as well as by wider surveys of the Rocky Flats area.

The topography of the site is simple (Figures 3 & 16) and seems reasonably characteristic of much of the western part of Rocky Flats. Further, the interrelated nature of geology, topography, soils and vegetation which is the normal pattern for Rocky Flats is found on the site (Figure 16). At the head of the valley side and in the lee of the pediment surface, the site includes a narrow (no more than 10 m wide) band on which drifting snow accumulates, occasionally to a depth of 50 cm. Most of the characteristics of this site are shown diagrammatically (Figure 16).

Figure 16

THE LINDSAY RANCH SITE

KEY: Vegetation 3 - Dry Communities; 4 - Wet Scrub, 6 - Moist Meadow, 7 - Streambank, 8 - Wet Marsh Vegt.
Geology: Qrf - Rocky Flats Alluvium, Early Pleistocene; Klu - Upper Laramie Formn., Cretaceous.

The flat, almost horizontal (under $1/2^{\circ}$ slope) pediment surface at the highest part of the site (Plots A and B) leads to a sharply convex change of slope (Plot C) at the top of the valley side. Below this change in slope is a roughly retilinear slope of 15.5° on which Plot D is located. At the foot of this straight slope is the surface contact of the Rocky Flats Alluvium and the shales of the Laramie Formation and downslope from here the valley side becomes concave and its slope flattens gradually to about 1° on 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 Laramie Formation 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 (Clark & Webber 1976). 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 becomes texturally finer (Figure 16) 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. This is particularly reflected in the moisture retention characteristics of the soil (Figure 11). The surface soil textures suggest an increase in frost susceptibility downslope but in the field situation this seems to be effectively counteracted by the vegetation cover. On the valley floor, the ground cover is almost 100% and segregation ice development has rarely been observed in the soils there.

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

1. its topographic similarity to large areas of the western part of Rocky Flats, including the area on which the Rocky Flats Plant is built;
2. the presence of bare soil areas on the pediment surface, suggesting a potential for frost action and wind erosion;
3. the simplicity and uniformity of the pediment surface around the head of the site which allows simplifying assumption about air flow across this part of the site.

THE STUDY PERIOD

The period 1974-1978 appears to have been fairly normal on the high plains of Colorado. At the Lindsay Ranch site on Rocky Flats, this is expressed in highly seasonal temperature and precipitation regimes and wide year-to-year variability in these characteristics. This variability is particularly evident in the record of frost events and their effect on the soil.

Precipitation

The four winters of record show good contrasts in precipitation totals: the first two were relatively wet, the last two much drier. This contrast, and its influence on the frequency of frost heave (through soil moisture) is shown in Tables 12 and 13. Almost all of the winter precipitation is in the form of snow which gives complications to an evaluation of its influence on frost action. Much snow is redistributed on the site by wind drifting and all of it is not immediately available as soil moisture. Instead, a variable interval occurs between the time of precipitation and the time when it becomes available as a liquid to form segregation ice in the soil. On the Lindsay Ranch site, snow accumulation tends to be greatest at the head of the slope (Plot C), just downwind of the change of slope at the pediment edge, and this has frequently been found to lead to a increased volume and frequency of segregation ice development in the soil there.

Frost

During the study, below freezing temperatures in the air at 1.5m height above the ground have been recorded in all months between September and May but at no time have they remained below 0.0°C for more than a few days consecutively. Thus, the frequency of below-zero temperatures is reflected in the number of freeze-thaw cycles which have a dominant diurnal (24 hour) period (Table 13). On average, about 100 such frost cycles per year can be expected on this site, though with a variability of $\pm 20\%$. The low frequency shown for 1974-1975 reflects a partial record and that for 1977-1978 is a partial response to truncation of the record in April and to an unusually warm spring (Table 12).

Table 12

WEATHER SUMMARY BY WINTERS

Winter	N (days)	Freeze-Thaw Screen	Cycles Surface	Heave Events	Precip. (mm)	Days of Wind > 40 mph
1974-75	155	77	22 (a)	6	111	N.D.
1975-76	218	102	100	29	154	60
1976-77	234	123	132	9	135	51
1977-78	176	76	51 (a)	8	62	40

Winter is defined as the October-April period.

Source: Records from Lindsay Ranch site.

Notes: a) Surface temperature record is available for only 59 days in 1974-75 and 135 days in 1977-78.

Table 13

WEATHER RECORDS: LINDSAY RANCH.

	<u>Freeze-Thaw Cycles</u>		<u>Temperature</u>	<u>Precip.</u>	<u>Days of Wind</u>
	<u>Screen</u>	<u>Surface</u>	<u>(°C)</u>	<u>(mm)</u>	<u>40 mph.</u>
Dec 1974	17		-0.45	9.0*	
Jan 1975	20		-1.55	15.5	
Feb	16		-2.32	22.8	
Mar	14	7	3.13	39.5	
Apr	8	15	4.54	24.0	
May	2	0	10.42	110.8	
Jun	0		16.14	38.1	
Jul	0		21.28	43.2	
Aug	0		21.61	40.0	1
Sep	0		13.84	13.7	1
Oct	3	0	10.62	25.5	1
Nov	11	13	2.94	31.8	11
Dec	7*	18	5.62*	7.6	12
Jan 1976	15	25	1.86	21.6	11
Feb	17	18	1.02	13.7	12
Mar	17	26	0.71	31.0	9
Apr	21	0*	3.82	22.4	4
May	11	0*	6.64	ND	2
Jun	0		12.06	ND	0
Jul	0		16.36	55.9	3
Aug	0		14.47	30.5	1
Sep	3		10.54	124.0	1
Oct	13	8	7.94	26.4	3
Nov	16	12	4.22	3.8	4
Dec	20	28	2.17	14.0	11

(Table continues on next page)

Table 13 (cont.)

WEATHER RECORDS: LINDSAY RANCH.

Jan 1977	25	20	-1.70	2.5	13
Feb	19	25	1.81	10.2	9
Mar	22	28	1.44	14.7	10
Apr	5	10	7.00	63.5	1
May	0	1	13.23	10.2	0
Jun	0	0	11.92	22.4	
Jul	0	0	12.17	52.1	
Aug	0	0	17.37	19.0	
Sep	ND	0	ND	3.0	
Oct	2	ND	12.00	7.6	
Nov	9	11	6.78	11.4	7
Dec	17	15	2.66	3.8	12
Jan 1978	18	17	-3.25	12.7	4
Feb	16	6*	-1.08	1.3	3
Mar	11	2	5.78	15.2	5
Apr.	4*	0	8.07*	21.6	9*

Notes: * indicates that only a partial record is available for that month.

ND No data available.

The seasonal pattern of freeze-thaw cycles is a simple one with a single maximum frequency in the fall. The 1976 and 1977 record suggests a secondary maximum in March and April but this is not reflected in the frequency at the ground surface (Table 13). On this evidence, the record does not support the suggestion of early-winter and spring peaks in frost frequency.

The record of surface heaving due to the growth of segregation ice in the soil does not match the pattern of freeze-thaw cycles (Table 12). In all, only 52 heave events were recorded at Plot B from 378 freeze-thaw cycles. This disparity suggests that, while freezing temperatures are necessary for soil heaving, they are not in themselves sufficient in this environment. In fact, the record of soil surface heave events shows a different seasonal pattern with peak frequencies in November (27% of all events) and March (42%) (Table 14). Inter-annual variations in heave event frequencies are also very much wider than those in other weather characteristics: the record shows 3 times as many in the 1975-1976 winter as in either of the two following winters (Table 12).

Wind Speeds

Continuous wind records are available for only the last 3 winters of the study period at the Lindsay Ranch site. As with the records for an earlier period from the Rocky Flats Plant (above), periods of high winds may be estimated from the frequency of daily maxima over 40 mph (18 m sec^{-1}) (Table 13.) These records are from an anemometer at 3 m above ground surface and so are not compatible with those used in the earlier analysis (above). Nevertheless, they show the same kind of seasonal pattern with greatest frequency in the months of December-January-February (about 1 day in 3 in this period) and a relatively constant annual frequency of about 50 days p.a. on which gusts exceeding this speed are recorded (Table 12).

Table 14

FROST HEAVE FREQUENCY: LINDSAY RANCH

Month	Record*	Surface Freeze-Thaw Cycles		Record*	Recorded Frost Heave	
		No.	%		No.	%
OCT	47	8	17.0	37	0	0.0
NOV	74	36	48.6	90	14	15.6
DEC	81	61	75.3	93	7	7.5
JAN	74	62	83.8	93	3	3.2
FEB	65	49	75.4	85	3	3.5
MAR	101	63	62.4	103	22	21.4
APR	101	25	24.8	120	4	3.3
MAY	39	1	0.6	12	0	0.0

* "Record" refers to the number of complete days in the record.

Source: Field observation from Lindsay Ranch, Plot B 1975-1978.

Combined Effects

Even the crude estimates provided by the averages of Table 13 are sufficient to show that no single weather characteristic is capable of accounting for frost heave events on Rocky Flats. They can, however, be used as the earlier one from the Rocky Flats Plant to estimate joint probabilities of events which may produce ice segregation in the soil. This requires the same assumptions that were made in the earlier analysis (above), in particular the independence and stationarity of the records. Table 15 presents the results of this analysis which are closely comparable to those obtained from the 1968-1974 record from the Rocky Flats Plant. Among other things, this comparability offers support to the suggestion that the period of study at the Lindsay Ranch site has not been atypical in terms of the weather conditions leading to frost action.

The product of the estimated probabilities of freeze-thaw activity and precipitation (Table 15) has a bimodal distribution with peaks evident in March and November (secondary). The extension of this to include the probability of high wind episodes is included in Table 15 but is not especially useful because the soil surface is known to retain a disturbed surface appearance for some time after each heave event (Field Survey of Frost Activity: above). This "memory", which may be as much as 10-15 days in length, clearly contradicts the assumption of stationarity and so the estimates in Column 5 of Table 15 must be treated with caution. They must be underestimated, perhaps by a factor of 10 or 15.

The freeze-thaw - precipitation product of Table 15 can also be compared to the empirical record of surface heave at Plot B at the Lindsay Ranch. The result is a surprisingly good match which suggests that the monthly frequency of heave events may be estimated from air temperatures and precipitation. (The estimated values are correlated to the observed frequencies of heave ($r = 0.860$, d.f. = 10) but tend to be underestimated in months when frost heave is most common) (i.e. November and March). This may reflect the influence of moisture storage, either on the ground surface as snow or in the soil, which is also evident in the clustering of heave events in time (see: Frost Heave Periods).

Table 15 EMPIRICAL PROBABILITIES: LINDSAY RANCH. 1974-1978

Month	Freeze-Thaw (1)	Precip. (2)	Wind (40mph)	Products (1x2) (1x2x3)		Recorded Heave.
Jan	0.67 (0.84)	0.10	0.34	0.07	0.02	0.065
Feb	0.62 (0.75)	0.10	0.32	0.06	0.02	0.047
Mar	0.62 (0.62)	0.19	0.27	0.12	0.03	0.194
Apr	0.44 (0.25)	0.21	0.16	0.09	0.01	0.033
May	0.14 (0.01)	0.23	0.06	0.03	0.002	0.0
Jun	0.0 (0.0)	0.15	ND	0.0	0.0	0.0
Jul	0.0 (0.0)	(0.11)	ND	0.0	0.0	0.0
Aug	0.0 (0.0)	0.15	0.07	0.0	0.0	0.0
Sep	0.06 (0.0)	0.18	0.04	0.01	0.0004	0.0
Oct	0.21 (0.17)	0.11	0.08	0.02	0.002	0.0
Nov	0.46 (0.49)	0.17	0.29	0.08	0.02	0.133
Dec	0.64 (0.75)	0.09	0.45	0.06	0.03	0.065

Source: Weather Records from Lindsay Ranch, 1974-1978.

Notes: Freeze-Thaw probabilities are estimated from screen temperatures with the equivalent estimates based on surface temperatures in parentheses.

Figure 17

PREDICTED AND OBSERVED HEAVE PROBABILITIES

All values are mean monthly estimates:

Observed values based on the heave record at Lindsay Ranch;

Predicted values derived as the product of monthly freeze-thaw and precipitation probabilities (Table 15).

Three months lie at the 0.0 ~ 0.0 intersection.

The 45° line is the line of perfect correspondence.

Source: Weather records from the Lindsay Ranch site, 1974 - 1978.

FROST HEAVE EVENTS

Most of the 52 frost heave events which have been recorded instrumentally on the Lindsay Ranch site have been described in earlier reports from this project (Caine et al. 1975, 1976, 1977). Those which have not been described occurred in the 1975-1976 winter, when most frost activity was recorded, and involved only small amounts of surface heave. They have been included here in summary statistics (Table 16) but contribute little to the evaluation of frost effects.

Instrumentation

Frost heave of the soil surface has only been recorded on a small (under 50 cm diameter) patch of bare soil at Plot B on the Lindsay Ranch site. The recording system consisted of a light wire foot of circular form resting on the soil surface and acting through a linear transducer interfaced with an Esterline-Angus recorder. This system allows a precision of ± 0.2 mm in the vertical (heave) dimension and ± 10 minutes in time. It should also be noted that it tends to underestimate the amount and frequency of heave for two reasons. First, the recording foot position has been constant throughout each winter and occasionally needle ice growth has been observed visually elsewhere on this part of the study site when none has shown on the record. Second, the resistance of the foot and transducer necessary to ensure its return as the ground settles after heaving means that the amounts recorded for any single heave event will be less than might have occurred in unrestricted conditions. On November 11, 1975, when 7.6 mm of heave were recorded instrumentally, ice needles up to 45 mm long were found in the neighborhood of the sensor at Plot B. This is an extreme case but may be indicative of the possible magnitude of underestimation in the heave record.

Other instrumentation on the study site has varied from winter to winter but has been intended at all times to define the local soil and atmospheric conditions at times of heave activity. In general, these records have only been maintained during the October - April season when frost can be expected. On Rocky Flats, except for some general weather records which have been continued throughout all 4 years. The instrumental array is summarized in Table 17, including the estimated precision for each record.

Table 16

RECORDED FROST HEAVE: LINDSAY RANCH

Event	Date	Start Time	Duration	Maximum Heave	Temp. At Start	Precip. Previous Day	Initial Heave Rate
1	29. 3.75	02:00	10 hr	2.6 mm	0.9°C	1 mm	0.5
2	30. 3.75	21:00	15	6.9	0.4	0	0.6
3	31. 3.75	24:00	10	5.5	-0.8	0	0.5
4	3. 4.75	20:00	15	6.0	-5.1	5	1.0
5	4. 4.75	02:00	7	5.2	-2.7	0	1.2
6	14. 4.75	24:00	8	8.7	-1.3	0	1.0
7	10.11.75	02:00	11	7.6	0.0	15	1.2
8	11.11.75	16:00	22	10.5	0.0	0	0.6
9	12.11.75	17:00	17	8.7	-1.0	0	1.7
10	13.11.75	03:00	6	1.4	-2.0	0	1.4
11	23.11.75	02:00	8	3.0	-.02	0	0.6
12	25.11.75	03:00	3	0.8	-.08	4	0.4
13	26.11.75	22:00	16	4.3	0.0	0	0.3
14	27.11.75	17:00	21	3.6	-1.3	0	0.3
15	28.11.75	17:00	20	3.9	1.0	0	0.5
16	29.11.75	22:00	13	3.1	-1.8	0	0.5
17	19.12.75	20:00	16	1.3	-0.5	(6)	0.3
18	20.12.75	18:00	19	2.6	-0.5	0	0.5
19	21.12.75	20:00	16	1.6	-1.3	0	0.4
20	22.12.75	18:00	16	0.5	-1.2	0	0.1
21	20. 1.76	02:00	9	0.8	0.0	0	0.2
22	21. 1.76	21:00	16	2.8	-0.8	0	0.4
23	22. 1.76	20:00	15	3.1	-1.0	0	0.3
24	24. 1.76	19:00	8	0.6	-1.0	0	0.2
25	26. 1.76	19:00	14	1.0	0.0	0	0.2
26	28. 1.76	20:00	12	1.3	-0.5	0	0.2
27	6. 3.76	24:00	9	0.8	-0.6	4	0.2
29	7. 3.76	02:00	9	0.8	-0.8	4	0.2
29	8. 3.76	19:00	16	5.2	0.0	2	0.3

(Table continues on next page)

Table 16 (cont.)

RECORDED FROST HEAVE: LINDSAY RANCH

30	11. 3.76	22:00	13	1.6	-1.0	0	0.4
31	12. 3.76	17:00	18	5.1	-1.5	0	0.5
32	14. 3.76	01:00	8	0.5	-2.6	0	0.1
33	15. 3.76	21:00	11	1.0	-3.0	0	0.2
34	29. 3.76	02:00	9	2.0	-1.4	11	0.4
35	30. 3.76	21:00	13	7.0	-0.6	1	0.2
36	14.11.76	22:00	11	1.0	0.0	0	0.3
37	11.12.76	20:00	14	1.3	-1.0	(5)	0.3
38	12.12.76	19:00	14	1.8	-3.0	0	0.3
39	14. 2.77	01:00	11	6.5	0.0	4	0.6
40	7. 3.77	03:00	6	1.5	1.0	0	0.2
41	10. 3.77	23:00	16	4.1	0.0	2.5	0.2
42	11. 3.77	18:00	15	5.0	-0.0	0	0.7
43	12. 3.77	23:00	9	2.5	-2.0	0	0.3
44	4. 4.77	24:00	9	4.3	-2.0	(12)	0.3
45	8.11.77	16:00	23	3.0	-1.0	2.5	
46	1. 2.78	17:00	19	0.4		0	
47	2. 2.78	19:00	14	0.6		0	
48	22. 2.78	22:00	13	0.9		0	
49	7. 3.78	01:00	8	2.1		1	
50	10. 3.78	03:00	6	1.7		1	
51	11. 3.78	05:00	3	0.7		1	
52	25. 3.78	03:00	6	1.1		1	

Frost Heave Periods

Even within the months when needle ice development is most likely, the time distribution of heave events is not a random one (which suggests the inadequacy of assuming stationarity as in the analysis of monthly weather records). This is best illustrated by the record from the 1975-1976 winter when 29 individual heave events occurred in 5 periods of up to 5 days each when heave was recorded on successive nights. The existence of runs in this record is clearly significant ($Z = 5.76$ on runs test) and defines a situation in which a single heave event greatly increases the probability of another one on the following day. Such a consecutive sequence of heave events is defined here as a "Frost Heave Period".

For the entire record, with 52 heave events, the average run length is approximately 2 days. This seems short but is influenced by the 15 occasions on which isolated heave events have been recorded: if these are omitted the average reflects the importance of precipitation (and usually snowmelt) in producing needle ice events on Rocky Flats. This is also evident in the fact that the amount of heave produced by successive events in the same frost heave period tends to decline with time, presumably as the soil moisture storage is depleted by evaporation from the surface. When the Frost Heave period exceeds 2 days in length, the decline in heave amounts can be estimated as a simple decay function of the form:

$$H_t = H_0 k^t$$

where H_t is the heave on day t ;

H_0 is the initial heave

and k is a decay constant (usually about 0.75).

This sequence is not usually maintained for many days but is usually truncated by a change in weather conditions: to more intense freezing of the soil or to warmer weather without freezing temperatures. Even without this truncation, the low value of k defines a rapid decline in the effectiveness of frost heave: from the maximum recorded in 4 years, it would decline to under 1 mm in only a week.

Table 17

INSTRUMENTATION: LINDSAY RANCH 1974-1978

Observation	Period*	Form	No. Plots	Precision
Air Temperature	12.74 - 4.78	c	1	$\pm 1^{\circ}\text{C}$
Rel. Humidity	12.74 - 4.78	c	1	$\pm 3\%$
Percipitation	12.74 - 4.78	c	1	$\pm 1\text{mm}$
Net Radiation	4.75 - 4.77	c	1	$\pm 0.05 \text{ ly min}^{-1}$
Air Temp. (15cm)	10.75 - 4.78	c	1	$\pm 0.25^{\circ}\text{C}$
Wind Speed (3m)	9.75 - 4.78	c	1	$\pm 1 \text{ mph}$
Wind Speed (0.5m)	9.75 - 4.77	c	1	$\pm 1 \text{ mph}$
Wind Direction	9.75 - 12.77	c	1	$\pm 15^{\circ}$
Soil Temperature:				
Surface	3.75 - 4.78	c	1	$\pm 0.25^{\circ}\text{C}$
2 cm	12.74 - 12.76	c	1	$\pm 0.25^{\circ}\text{C}$
5 cm	10.75 - 4.78	c	1	$\pm 0.25^{\circ}\text{C}$
10 cm	3.76 - 5.76	c	1	$\pm 0.25^{\circ}\text{C}$
15 cm	12.76 - 4.78	c	1	$\pm 0.25^{\circ}\text{C}$
Soil Heave	3.75 - 4.78	c	1	$\pm 0.2^{\circ}\text{C}$
Soil Moisture				
5 cm	1.75 - 4.77	p	3	$\pm 5\%$
10 cm	1.75 - 4.77	p	3	$\pm 5\%$
20 cm	1.75 - 4.77	p	3	$\pm 5\%$
Soil Temperature				
2 cm	12.74 - 4.77	p	1	$\pm 0.5^{\circ}\text{C}$
5 cm	12.74 - 4.77	p	1	$\pm 0.5^{\circ}\text{C}$
10 cm	12.74 - 4.77	p	3	$\pm 0.5^{\circ}\text{C}$
20 cm	12.74 - 4.77	p	3	$\pm 0.5^{\circ}\text{C}$

Notes: Most records are not continuous through the summer months (May-September) and short periods may be missing at other times because of instrument or recorder failure.

c refers to a continuous record.

p refers to periodic observation only.

The occasions when a decline in heave amounts does not occur on successive days are usually found at the start of a frost heave period, particularly when it involves heaving of the soil under a shallow snow cover. In these situations, the second day of the frost heave period usually shows the greatest amount of heave which seems to reflect the continued supply of water to the surface soil from snowmelt.

In this enquiry, the definition of frost heave periods has further importance because it demonstrates a lack of statistical independence among frost heave events. With only 52 recorded events in 4 winters, and this lack of independence, the statistical sample of frost heave events is quite small. Since the average length of a frost heave period is 2 days, it would probably be best to reduce the degrees of freedom in testing to about half in order to take this bias into account.

The Normal Heave Event

The average conditions under which frost heave occurs at Rocky Flats are not especially useful in defining the control of soil disturbance but some general comments may be derived from Table 16. These are then amplified by reference to two different frost heave periods in the record. Other heave events have been described in earlier reports of this project (Caine et al. 1975, 1976, 1977).

The characteristics of frost heave due to needle ice growth on the upper part of the Lindsay Ranch site (Plot B) may be summarized in 7 comments:

- 1) The normal heave event is a diurnal phenomenon with a duration of 10 to 12 hrs in which lifting of the soil surface occurs over 7 hrs and is followed by settling over a period of 3 to 4 hrs. This cycle tends to start at between 20:00 hrs and 24:00 hrs with maximum heave occurring at about 07:00 hrs (approximately local sunrise). This marked asymmetry during development is obvious in almost all heave events and can be shown diagrammatically (Figure 18). It appears to reflect the energy required to draw water to the freezing plane and the lower requirements for its melting at a later time.
- 2) The recorded amounts of frost heave due to needle ice growth are slight: over 4 winters the maximum recorded was only 10.5 mm with an average from 52 events of 3.1 mm. The fact that these are minimal estimates should, however, be remembered.

- 3) During the heave part of most events, heave rates are not constant (Figure 18). Instead, they decline through time: in the first hours of heave they average about 0.49 mm hr^{-1} . The declining heave rate reflects the increased tension with which water is held in the soil below the freezing plane as it is progressively removed during ice segregation.
- 4) The total amount of heave recorded in any event reflects the moisture status of the soil close to the ground surface at the time that heave commences. In most cases, this moisture appears to be held at low tensions (more than 25% water content, i. e. equivalent to tensions of less than 0.1 bar (Figure 11)) in the uppermost 10 cm of soil. However, since soil moisture has not been monitored continuously in the study, this correspondence is not well tested by available data though it is suggested by 3 separate observations. First, there is a significant correlation between heave amounts and the water content of the soil at 5 cm on the occasions when the latter was measured prior to a frost heave event ($r = 0.519$, $N = 17$). Second, on many occasions, and especially at the start of frost heave periods, the observed heave amount is about the same as the precipitation recorded on the days leading up to a heave event (Table 16). This suggests that recent precipitation, or snowmelt, is the immediate source of the moisture in needle ice in this environment. Third, the decline in heave amounts during frost heave periods appears to be due to depletion of a soil moisture reservoir through time. The fact that this is defined in a period of 2 to 3 days supports the contention that needle ice growth depends upon a source of moisture at shallow depth in the soil with only slight total volume of water.
- 5) In addition, the amount of heave tends to reflect the duration of the heave event. This correspondence is less close than that to the moisture source but is nevertheless defined by a weak, but significant, correlation between the heave amount and the duration of the rising part of the heave cycle ($r = 0.290$, $N = 52$).
- 6) During heave events, soil temperatures always define an upward (toward the surface) gradient and heat flux. Heave usually starts soon after the surface temperature falls to slightly below freezing (mean temperature = -0.8°C , based on 51 cases excluding Case 4). Table 16 does, however, show a wide variance in

Figure 18

A GENERALIZED FROST HEAVE CYCLE: LINDSAY RANCH SITE

this characteristic which may be due to the 10 - 20 cm separation of the heave sensor and surface thermistor, resistance to movement in the heave sensor or use of a coarse time resolution. At the start of heave, the soil temperature at 5 cm depth is usually $2^{\circ} - 3^{\circ}\text{C}$, or more, above freezing, and remains above freezing throughout the event.

7) With the available sample of heave events, it has not been possible to define seasonal changes in the nature of needle ice growth. Such changes may be expected to reflect changes in radiation receipts, in the timing of sunset and sunrise and in soil moisture but they are masked by the wide variance of heave characteristics shown in Table 16.

Heave Events 7, 8, 9, & 10

Most of the heave events of Table 16 have been described individually in earlier reports from this project (Caine et al. 1975, 1976, 1977) and so are not treated here. Two frost heave periods have, however, been chosen to illustrate the nature of needle ice effects in the Rocky Flats environment. The first of these is composed of Events 7, 8, 9 and 10 which occurred on successive days in mid-November 1975. The basic characteristics of these four events are summarized in Figure 19 and Tables 16 and 18.

The frost heave period of mid-November 1975 started at 01:20 hrs on November 11 as the soil surface temperature fell to below 0°C and heaving of the surface commenced. In the first event of the period, this led to a maximum heave of 7.6 mm at 08:00 hrs. In the two days prior to this, 16.1 mm of precipitation had been recorded at the Lindsay Ranch site, this is probably a serious underestimate of the true amount since it fell as snow. Above-freezing soil temperatures suggest continuing melt of the snow cover and movement of the meltwater into the soil. Throughout the event, the soil surface temperature remained close to 0°C and freezing penetrated to no more than 1 cm depth. Settling of the heaved surface started soon after local sunrise as the soil surface temperature rose to above-freezing levels, and to 5°C by 11:00 hrs when settling was complete. At this time, the soil retained a residual heave of about 1 mm (equivalent to about a 10% increase in bulk for the soil affected by freezing).

Figure 19

FROST HEAVE EVENTS 7, 8, 9 & 10
NOVEMBER 10 - 14 1975

The second event of the period started at 17:00 hrs on November 11 and is one of the longest in the Rocky Flats record (22 hrs total duration). Once again, heave started as the soil surface temperature fell below 0°C and continued to about local sunrise. A greater heave displacement (10.5 mm) in this event is associated with a longer duration of freezing than in the previous one (14 hrs compared to 6.5 hrs) for the initial rates of heave are similar in both cases. The greater duration of freezing also produced lower temperatures in the soil with freezing recorded at 2 cm depth from 03:00 hrs to 12:00 hrs. 6 hrs were needed for settling from this heave but was practically complete in the first 3 hrs of these. This left a further 1.8 mm of residual heave (in addition to that due to the previous event): again about a 10% increase in bulk.

The frost heave period continued on the following evening when the surface temperature again fell below 0°C at 17:30 hrs. This event shows a pattern similar to that of the previous one, though with a lower initial heave rate so that the maximum heave (8.7 mm) was eventually less. Very rapid heating of the soil surface brought its temperature to 0°C and caused settling from 06:40 hrs on. About 2.3 hrs were sufficient to allow complete settling and no additional residual heave was retained on this occasion (about 2.8 mm was retained from the two previous events).

The frost heave period was closed by a very short event which started at 04:00 hrs on November 14. This shows many of the characteristics of the earlier events but had only a short duration (3 hrs to peak heave) and produced only 1.4 mm of surface displacement. Settling commenced at about 07:15 hrs and was completed in slightly over 30 minutes, leaving no further residual heave.

This frost heave period offers a useful illustration of the controls and characteristics of needle ice development and soil disturbance at Rocky Flats. Briefly these are:

- 1) The freezing temperature, both heave and settling start within 30 minutes of the soil surface temperature crossing 0°C ;
- 2) The effect of the duration of freezing on the amount of heave;
- 3) The importance of prior precipitation and a high soil moisture content;
- 4) The shallow depth of influence of freezing at times of needle ice growth (about 2 cm at the most in this case);

Table 18

FROST HEAVE PERIOD: NOVEMBER 1975

Conditions at Start of Heave

Event	7	8	9	10
Time	01:00	17:00	17:30	04:00
Air Temp.	-0.3°C	-3.0	-2.2	7.0
Air Rel. Humidity	45%	35%	40%	25%
Surface Temp.	0.0°C	-1.0	-1.0	-1.0
Soil Temp 2 cm	2.6°C	2.0	2.0	3.0
Soil Temp 5 cm	8.0°C	7.0	7.0	8.0
Wind Speed (3m)	63 mph	38	8	7
Wind speed (0.5m)	43	24	4	4
Temp. Gradient	-1.6°Ccm ⁻¹	-1.6	-1.6	-1.8
Initial Heave Rate	1.8mm hr ⁻¹	2.4	0.9	0.4

Conditions at Start of Settling

Event	7	8	9	10
Time	08:15	07:45	06:40	07:15
Air Temp.	-1.9°C	-2.1	7.0	8.5
Air Rel. Humidity	25%	35%	20%	20%
Surface Temp.	0.0°C	-1.7	-0.5	-0.5
Soil Temp 2 cm	1.0°C	0.0	1.0	2.0
Soil Temp 5 cm	7.0°C	6.0	7.0	7.0
Wind Speed (3m)	47 mph	21	16	9
Wind Speed (0.5m)	36 mph	15	14	6
Temp. Gradient	-1.4°Ccm ⁻¹	-1.5	-1.5	-1.5
Initial Settling Rate	1.0mm hr ⁻¹	1.0	1.8	1.4

Notes: Temperature gradient (°Ccm⁻¹) is estimated for the upper 5 cm of soil and is negative when directed toward the surface.

Initial heave rate is the rate (mm hr⁻¹) during the hour after the start of heave.

Initial settling rate is the rate (mm hr⁻¹) during the hour after the start of settling.

5) The reduction of heave amounts with successive events in the same frost heave period.

In addition, this frost heave period has some unusual features, in particular because it shows needle ice development under relatively windy conditions (Event 7). This is contrary to the experience of workers in other environments (e.g. Outcalt 1969) who have found wind to preclude needle ice growth. This disparity can only be explained by the relatively sheltered nature of the study site at the Lindsay Ranch on a micro-scale, i.e. the affected bare soil areas are no more than 50 cm across and are surrounded by grasses that are almost as high.

Heave Events 41, 42, & 43

The second frost heave period described here (Figure 20, Table 19) occurred between March 10 and 13, 1977. This sequence has many similarities with that of November 1975 described above, and a few contrasts also. Like the earlier one, it was triggered by snowfall, in this case 3 mm (water equivalent) were recorded during the early afternoon of March 10 and soil heave commenced about 5 hrs later. Since ground temperatures were above freezing during the snowfall, melting would have provided moisture to the soil almost immediately.

The first heave event of the period started at 23:00 hrs on March 10 below a thin snow cover which maintained a constant ground surface temperature at 0°C. This snow cover also allowed heaving to continue after sunrise (maximum heave of 4.1 mm did not occur until 10:00 hrs) and retarded the settling rate (settling was not completed until 15:30 hrs). As in other events, soil temperatures remained above freezing throughout and heave and settling commenced as the surface crossed the freezing isotherm. Only a slight thickness of soil (under 1 cm) seems to have been affected by this event and the amount of residual heave after settling was only 0.7 mm.

The second event of the period followed soon after the end of the first: only 2 hrs separate the end of settling from Event 41 and the start of Event 42. This event, too, may have started under a thin snow cover but the rapid settling which started at 07:10 hrs on March 12 suggests that the snow

Figure 20

FROST HEAVE EVENTS 41, 42 & 43

MARCH 10 - 13 1976

11 Mar.

-99-

13 Mar.

12 Mar.

Table 19

FROST HEAVE PERIOD: MARCH 1977

Conditions at Start of Heave

Event	41	42	43
Time	23:00	17:40	22:20
Air Temp. (180cm)	-2.7°C	0.0	5.0
Air Rel. Humidity	100%	40%	20%
Air Temp. (15cm)	-2.2°C	0.0	0.0
Surface Temp.	0.0°C	0.0	-2.2
Soil Temp. 5 cm	1.8°C	1.0	3.8
Soil Temp. 15 cm	3.0°C	2.2	4.7
Wind Speed (3m)	27 mph	13	3
Wind Speed (0.5m)	9 mph	3	1
Temp. Gradient	-0.4°Cm ⁻¹	-0.2	-1.0
Initial Heave Rate	0.5mm hr ⁻¹	0.5	0.2

Conditions at Start of Settling

Event	41	43	43
Time	10:35	07:10	06:40
Air Temp. (180cm)	-1.0°C	1.0	5.0
Air Rel. Humidity	40%	25%	35%
Air Temp. (15cm)	-0.5°C	1.8	6.2
Surface Temp.	0.0°C	-2.2	0.5
Soil Temp. 5 cm	1.2°C	0.0	1.0
Soil Temp. 15 cm	2.2°C	1.7	2.0
Wind Speed (3m)	13 mph	12	3
Wind Speed (0.5m)	4 mph	3	0
Temp. Gradient	-0.2°Cm ⁻¹	-0.4	-0.1
Initial Settling Rate	0.6mm hr ⁻¹	2.4	1.5

Notes: Temperature gradient (°Cm⁻¹) is estimated for the upper 5 cm of soil and is negative when directed toward the surface.

Initial heave rate is the rate (mm hr⁻¹) during the hour after the start of heave.

Initial settling rate is the rate (mm hr⁻¹) during the hour after the start of settling.

cover was insufficient to interfere with surface heat exchange at that time. Following settling from Event 42, no additional residual heave was recorded although the surface remained about 0.5 mm above its level prior to Event 41.

The final event of the period followed very warm conditions on March 12 (when air temperatures reached 9°C) which are reflected in the soil and air temperatures of Table 19. Such high temperatures retarded the onset of frost heave and reduced the amount and rate of heave in two ways: through evaporation from the soil surface and by limiting the duration of the heave cycle. Again, settling of the soil surface was rapid and commenced at local sunrise as net radiation became positive and surface temperatures rose to 0°C . March 13 gave even warmer conditions than the previous day (maximum air temperature of 17°C and minimum of 0°C) which effectively terminated this frost heave period. Further frost heave did not occur until after precipitation on April 2, 1977.

The March 1977 frost period supports the conclusions drawn from that of November 1975 about the nature of needle ice events at Rocky Flats. It re-emphasizes the importance of precipitation prior to heave and indicates the correspondence between the amount of moisture provided and the magnitude of heave. In this case, 3 mm of recorded (probably underestimated) snowfall produced a maximum of 4.1 mm of heave, in the earlier case, 15 mm of precipitation preceded 10.5 mm of heave. In combination with the November 1975 frost heave period, it also suggests the importance of near surface soil temperature gradients: a steeper gradient is associated with more rapid rates of heaving. This is constant with what is known of the influence of temperature gradients on water movement through soil (e.g. Hillel 1971, p. 197).

Frost Heave at Rocky Flats

By way of summary, the basic environmental controls of soil disturbance by segregation ice, as defined empirically by this study, are presented here. These can be stated in a set of 5 conclusions:

- 1) Soil temperatures are clearly limiting of frost action but not in a simple way. Frost heave and ice segregation only occurs with freezing temperatures at the soil surface and above-freezing temperatures below that. During heave, the

freezing plane rarely penetrates below 2 cm depth in the soil and heave is inhibited by frozen ground below that depth.

2) A high liquid water content is necessary in the upper 5 cm of the soil (few recorded heaves occur if the water content at 5 cm is less than 25% by weight, most require at least 30%). On other hand, soil moisture below 5 cm depth appears unimportant to heave.

3) Contrary to the suggestions of other workers, high winds and a shallow snow cover have not proven limiting to soil heave. A snow cover can, however, change the timing of heave events by its interference with the normal energy exchange of the surface.

4) The amount of frost heave, and therefore the amount of disturbance, is also controlled by the duration over which ice segregation continues, the temperature gradient in the upper part of the soil, and the volume of soil water available there. The last is a reflection of prior precipitation and/or snowmelt which then acts as a limit to the total amount of heave possible in any event.

5) Finally, the quantitative estimates of soil disturbance by needle ice growth are relatively slight. The residual heave which is retained by the soil after a freeze-thaw cycle is usually shown as a 10 - 15% increase in the bulk (or the equivalent decrease in density) and is restricted to the surface 1 cm of soil. However, as with the measured heave, this will be underestimated because of the need to ensure the return of the heave sensor as the soil settles. It does indicate the spatial scale of the effects of needle ice growth: a scale of centimeters. This has seriously impeded attempts to measure directly changes in soil surface roughness and shear strength during the project.

SOIL SURFACE CHARACTERISTICS

The small scale of the changes in the soil surface that are induced by needle ice growth (e.g. Figure 2b) makes it difficult to define them in a quantitative way. Qualitatively, they are readily recognized and used to define areas prone to frost action, as in the broad-scale surveys reported earlier. Two different approaches to quantifying these changes were attempted during the study at the Lindsay Ranch, though neither were especially successful.

First, we have attempted to measure directly the microtopography of the soil surface where it is affected by frost action and so estimate changes in its surface roughness from successive surveys. Second, the direct measurement of the strength of the surface soil by instrumental means has been attempted. These two are treated in order here.

Soil Roughness

The surface topography of 1 m x 1 m plots on the study site has been measured by a rigid plexiglass frame equipped with measuring rods (Figure 21). At the time of measurement, this is mounted on permanently installed corner posts (assumed stable) and then forms the arbitrary datum plane from which the soil surface is measured. Observations have been made on a 20x20 point square grid which gives a spatial resolution of the observations of 5 cm. In the vertical dimension, measurements are made to ± 0.5 mm.

The results obtained from this experiment can be illustrated by reference to the observations made on each side of the mid-November 1975 frost heave period. This offers the maximum soil surface heave recorded during the study and is described in the previous section (Heave Events 7, 8, 9, & 10). Table 20 is a statistical summary of the observations from Plot B1, near to the heavily instrumented plot on the interfluvial at the Lindsay Ranch site, on 3 occasions in October and November 1975. The last of these surveys was made on November 17, only 3 days after Event 10, when the effects of segregation ice growth were still clearly visible at the soil surface.

The surface topography of the plot has not been greatly changed by frost action (compare the results for October 29 and November 17 in Figure 22). The only change that can be statistically defined is that in the general surface elevation. Following the frost heave period, the mean elevation is 2.1 mm higher than on the earlier occasion which corresponds surprisingly well to the 2.5 mm of residual heave shown in the heave record for the mid-November period (recorded on a different bare soil area in the same vicinity). The other statistics in table 20, based on the higher moments of the distribution, should be more diagnostic of small scale topographic roughness (rather than absolute topographic height) and these show no change between the observations.

Figure 21

MICROTOPOGRAPHIC MEASUREMENT

The frame consists of 2 parallel sheets of plexiglass with holes drilled on a 5 cm spacing and is temporarily mounted during measurement on permanently installed posts at each corner. Pins inserted through the holes allow the ground surface topography to be measured by reference to an arbitrary datum plane (the top plexiglass sheet).

Table 20

MICROTOPOGRAPHIC ROUGHNESS: PLOT B, 1975

Date	20 Oct.	29 Oct.	17 Nov.
Mean Elevn.	79.70 mm	78.48	80.58
Variance	104.25 mm ²	92.31	91.40
S.D.	10.21 mm	9.61	9.56
Skewness	-0.165	-0.172	-0.022
Kurtosis	2.821	2.903	2.877

All values are above an arbitrary base.

Measurement from a 20 x 20 grid with 5 cm spacing.

All estimates are based on a sample of 400 points

A test of the homogeneity of the variances for before and after the frost heave period gives an F value of 1.01, with 399 and 399 degrees of freedom. Even with the large number of degrees of freedom, this proves non-significant and, in any case, the change is toward a lower variance on November 17 (i.e. to a reduced roughness at that time). Similarly, the skewness and Kurtosis of the elevations do not change significantly during this period of 4 weeks.

It seems clear that, defined on a spatial scale of 5 cm, it is not possible to detect a quantitative change in the soil surface roughness during frost heaving: the visually evident changes are made on a smaller scale than this and so are not detected by this approach. Similar results were obtained on the other occasions when measurements were made although the November, 1975 case is the one that is most easily keyed to a specific set of frost heave events.

Soil Strength

The mechanical strength of the surface 1 - 2 cm of soil has been measured intermittently during the 1975-1976 winter by two instruments: a pocket penetrometer and a small shear vane. Both of these offer a better spatial precision than that available in the measurement of surface roughness: between 1 - 2 cm. They do, however, measure different characteristics of the soil and are based on different forms of induced failure and so results from the two tests are not directly comparable. The pocket penetrometer gives an estimate of resistance to penetration in the uppermost 5 mm of soil while the vane test used here provides a measure of lateral shearing strength at a depth of 1 cm below the soil surface.

Table 21 summarizes typical results from these tests obtained from the Spring of 1976 and defines a situation of extreme variability on a very small scale. The coarse, poorly sorted nature of surface materials on the interfluve at the Lindsay Ranch probably accounts for much of this variability: both of the instruments used in measurement are susceptible to gravel fragments in the soil.

Figure 22A MICROTOPOGRAPHY PLOT B 29 Oct. 1975

Figure 22B MICROTOPOGRAPHY PLOT B 17 Nov. 1975

Table 21 CHANGES IN SOIL SURFACE STRENGTH: SPRING 1976

Date	Statistic	Pocket Penetrometer	Shear Vane
22 Mar 1976		39	0.9
		680	0.2
		26	0.45
8 Apr 1976		58	0.62
		448	0.08
		21	0.29
15 Apr 1976		39	1.1
		63	0.32
		8	0.57

Notes: All estimates based on 30 observations

Values: Pocket Penetrometer - $1b \text{ ft}^{-2}$, resistance to penetration.

Shear Vane - $1b \text{ ft}^{-2}$ ($\times 100$), shearing resistance.

$t = 2.9$ (22/3 rs 8/4) Vane Shear 58 df

$t = 3.15$ (—— " ——) Penetrometer 58 df

The variations through time shown in Table 21 (over a period which included 2 heave events, one of which produced 7 mm of surface heave) do not offer strong support for the hypothesis that frost action leads to a weakening of the surface soil. This is particularly evident in the results obtained by penetrometer measurements which define, if anything, an increase in strength, though with a very high variance in all cases. Shear vane observation are more supportive of the hypothesis and show a 30% reduction in the shear strength of the surface soil with a recovery at a later date. In this case, the reduction is a statistically significant one ($t = 2.9$ with 58 degrees of freedom), though it must be noted that the test is based on inhomogeneous variance estimates.

In total, the evidence of Table 21 (a fairly typical set of observations) does not suggest that changes in soil resistance can be detected instrumentally in the Rocky Flats soils and confidently ascribed to the influence of soil freezing.

WIND CONDITIONS

At Lindsay Ranch site, wind speed records have been maintained for the period of study at two heights: 300 cm and 50 cm above the surface. Although these are not sufficient for a detailed analysis of the wind structure on this site, and were not intended for that, they do allow some analysis which may be interpreted in terms of wind erosion potential. This is considered here with reference to average conditions only.

The Mean Wind Profile

The characteristics of air flow that are of interest in soil erosion may be estimated from measured wind speeds assuming the logarithmic velocity profile (Sutton 1955; Plate 1971). This model is frequently used, although its use does require 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 the subject of this analysis and 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 (300 cm). However, it is doubtful if winds from other directions would meet the requirements because of topographic changes to the east and southeast. Fortunately, winds from these directions are relatively uncommon and so have been omitted from this analysis.

A final problem for this analysis derives from the fact that only two anemometer heights have been used in data collection. This makes it impossible to test the adequacy of the logarithmic model, or the temporal stability of the records.

In estimating individual wind profiles, instantaneous speeds (i.e. within the response time of the anemometer and recorder system: about 5 sec) have been used. For this, individual gusts have been identified on both records which avoids the uncertainty associated with the use of timing marks and time calibration of recorders. For each period of relatively high wind, 25 such pairs of gust speeds (one from each anemometer) form the sample of wind profiles. From each pair, the wind characteristics used here were derived and later averaged for the sample.

Two characteristics of interest to the study of wind erosion are evaluated here. Since both are estimated as averages for a period of up to 12 hrs, 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) (Lyles & Woodruff 1972) which are not easily estimated from the limited data available to this study. 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 (Figure 23). V_* provides an estimate of the horizontal shearing stress in the moving fluid

Figure 23

THE IDEAL WIND PROFILE

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 (Figure 23).

With anemometers at 50 cm. and 300 cm, Z_0 is estimated by:

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

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

Variations in the average values of Z_0 for the entire period of continuous wind records at the Lindsay Ranch are shown in Figure 24 and Table 22. This record shows a repeated annual cycle which reflects seasonal changes in the vegetation on the site. During the summer Z_0 is relatively high (more than 5 cm) but of comparable value to that found in studies over similar terrain elsewhere (Sutton 1955; Plate 1971). This is, of course, the season when the ground cover is best developed and at its greatest vertical extent. During the fall and winter, Z_0 is reduced to values of less than 2 cm. This appears to be a response to modification of the ground cover through breakage and flattening due to the wind and snow (any increase in soil roughness due to frost effects would not be sufficient to override the vegetative influence on this site). In April the cycle is brought to a close when the vegetation commences growth and, consequently, Z_0 rises back to values approaching 10 cm.

Although the empirical data base is not strong, some general comments about the variations in Z_0 can be made. First, the seasonal cycle defined in Figure 24 and Table 24A suggests that, in conditions like those found on the Lindsay Ranch site where individual patches of bare ground are of limited horizontal extent, the potential for wind erosion should be maximized during the winter months, including the periods when needle ice activity is most intense. This may not, of course, be true elsewhere on Rocky Flats where bare ground

Figure 24

TEMPORAL CHANGES IN THE ROUGHNESS LENGTH
LINDSAY RANCH SITE

Table 22

WIND CHARACTERISTICS: LINDSAY RANCH

Date	$\bar{V}$	$\bar{V}$ gust	z_0	V_*
9. 9.75	7	21.1	3.54	0.872
26. 9.75	9	18.4	2.90	0.720
8.10.75	5	54.3	0.79	1.583
22.10.75	7	16.8	0.85	0.506
10.11.75	7	42.7	0.18	1.158
1.12.75	29	60.3	0.54	1,806
16.12.75	9	35.6	0.70	1.094
4. 1.76	9	25.0	0.66	0.744
15. 1.76	26	47.9	0.74	1.478
30. 1.76	18	49.6	0.59	1.471
14. 2.76	13	33.6	0.92	1.017
1. 3.76	10	29.4	0.33	0.835
13. 3.76	15	27.0	0.53	0.780
2. 4.76	7	16.2	1.60	0.603
13. 4.76	14	34.4	1.53	0.760
25. 4.76	7	21.7	1.53	0.760
11. 5.76	9	25.0	1.48	0.828
14. 5.76	7	16.5	1.12	0.530
29. 5.76	3	14.2	4.50	0.598
9. 6.76	5	11.7	5.68	0.542
1. 7.76	6	17.0	8.74	0.856
18. 7.76	6	16.5	7.21	0.780
3. 8.76	4	11.7	4.08	0.522
20. 8.76	7	22.1	6.29	1.081
26. 8.76	9	23.3	5.06	1.071
14. 9.76	7	14.0	4.05	0.646
1.10.76	8	18.1	8.46	0.846
14.10.76	10	25.5	3.31	1.030
1.11.76	6	22.8	2.30	0.872

Table 22(cont.)

WIND CHARACTERISTICS: LINDSAY RANCH

Data	$\bar{V}$	$\bar{V}_{gust}$	Z_0	V_*
14.11.76	4	21.2	1.51	0.782
29.11.76	17	35.2	1.17	1.160
13.12.76	5	22.9	2.12	0.836
28.12.76	22	41.9	1.06	1.378
18. 1.77	17	38.1	0.91	1.204
27. 1.77	28	42.2	0.80	1.296
13. 2.77	12	35.5	1.16	1.177
23. 2.77	32	55.6	0.72	1.652
7. 3.77	13	28.2	1.05	0.900
20. 3.77	14	41.0	0.68	1.211
10. 4.77	10	19.0	2.88	0.727
26. 4.77	6	16.7	2.05	0.634

$\bar{V}$ is the mean wind speed at 300 cm height on the day concerned
(20 minute interval for 24hrs.) (mph)

$\bar{V}_{gust}$ is the mean of the gust velocities at 300 cm height used in
estimating Z_0 and V_* ($n \approx 25$ in all cases) (mph)

Z_0 is the mean of about 25 estimates based on gust velocities (cm)

V_* is the mean of about 25 estimates based on gust velocities ($m \text{ sec}^{-1}$)

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

Z_0 also appears to be slightly dependent upon the wind speed (Table 22). When the entire record is considered, the correlation is quite high but is undoubtedly influenced by a confounding of the seasonal variations in Z_0 and V_{300} . Removing this effect by considering seasons separately clearly lowers the correlations although the relationship remains consistent in form (Table 23). The relationship itself may be explained by a "smoothing" of the surface as the wind speed increases and flattens the vegetation.

Another reduction in Z_0 occurs in response to a snow cover. This influence was most marked in the 1975-1976 winter (e.g. in the observations for November 10 and March 1 when Z_0 was estimated at 0.18 and 0.33 cm respectively). The second winter of wind records (1976-1977) was an unusually dry one in Colorado and so this effect was not so evident then. This smoothing is also associated with a "lifting" of the effective ground surface by the thickness of the snow cover and so is even more marked than Table 22 suggests. At times with a continuous snow cover, Z_0 must be overestimated by an unknown amount in the calculations used here.

The change in Z_0 associated with a snow cover is important to this study and so is worth emphasizing, in spite of the imprecision with which it is estimated. For example, it means that the erosion of snow particles during drifting occurs from a smoother-than-normal surface. This is not the condition under which soil erosion might be expected to occur and forms another point of basic difference between snow and soil entrainment into the air flow (in addition to the difference in density of the two materials). Further, it is clear from Figure 24 that the reduced value of Z_0 is not maintained after removal of the snow cover.

Table 23

RELATIONS BETWEEN GUST VELOCITY AND Z_0

	n	r	a	b
Winter 1975-76	13	-0.492	2.252	-0.0347
Summer 1976	13	-0.352	6.655	-0.1377
Winter 1976-77	13	-0.614	5.843	-0.1184
Entire Period	41	-0.585	5.256	-0.1019

The simple linear model is used:-

$$Z_0 = a + bV_{300}$$

where

Z_0 is the roughness length (cm);

V_{300} is the gust velocity (mph) at 300 cm above ground surface.

Table 24 SEASONAL CONTRASTS IN WIND CHARACTERISTICS

A. Roughness Length (Z_0)

	Mean	Variance	Variance Ratio
Winter 1975-76	1.021	1.010	6.169 (p 0.01)
Summer 1976	4.067]	6.231	1.412 (N.S.)
Winter 1976-77	1.942	4.412	

Analysis of Variance

	S.S	d.f.	M.S.	F
Within Season	139.83	36	3.88	8.17 (p 0.01)
Between Season	63.45	2	31.72	
Total	203.28	38		

B. Relationship between V_* and V_{300}

	Mean	Variance	Variance Ratio
Winter 1975-76	3.195×10^{-2}	0.244×10^{-4}	3.24 (p 0.05)
Summer 1976	3.495×10^{-2}	0.793×10^{-4}	3.46 (p 0.05)
Winter 1976-77	3.417×10^{-2}	0.229×10^{-4}	

Analysis fo Variance

	S.S	d.f	M.S.	F
Within Season	14.41	35	0.412	0.74 (N.S.)
Between Season	0.61	2	0.306	
Total	15.02	37		

(S.S. and M.S. $\times 10^{-4}$)

The Friction Velocity

The amount of shearing in the air flow clearly varies with the absolute wind speed (e.g. with the gust velocity at 300 cm: Table 22 and Figure 25). Unlike Z_0 , however, this relationship between V_* and V_{300} is apparently invariant with ground conditions, at least as these are reflected by the season (Figure 26). The only exception to this may be found in the variability of the regression coefficient (b) defining the relation. The variance of (b) seems to increase in the summer: $F = 2.42$ with 10 and 27 degrees of freedom on a variance homogeneity test (omitting the estimate of (b) for August 20, 1976). The increased variability of (b) in summer (with no change in its mean value: Table 24B) suggests the influence of the vegetation, particularly on the anemometer at 50 cm height which at that season is almost within the canopy. Some evidence for a weak inverse correlation between (b) and V_{300} in the summer season ($r = -0.374$ with 11 degrees of freedom) offers further support to this contention. It is also supported by the influence of the higher wind speeds of summer on Z_0 described above. In all, it appears that the bending of the vegetation at higher wind speeds reduces the difference in velocities recorded at 50 and 200 cm heights (V_* is derived from this difference).

However, V_* is only important when related to the soil at the ground surface and so it is useful to introduce the concept of a critical friction velocity (V_{*T}). 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 previously 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 (Lyles and Wooduff, 1972). Nevertheless, it offers a first approximation of the probability of wind erosion which maybe useful if not extended too far. 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 Lindsay Ranch site, ϕ_{20} is approximately 2 mm which suggests a threshold shear velocity

Figure 25

THE V_* - WIND SPEED (3 m) RELATIONSHIP
LINDSAY RANCH SITE

Figure 26

TEMPORAL CHANGES IN THE V_* - WIND SPEED
RELATIONSHIP

of 0.65 m. sec^{-1} (Bagnold, 1944, p. 88). This is equivalent to a velocity difference of about $6 \frac{1}{2}$ mph between the anemometers at 300 cm and 50 cm above the ground.

This is not a high value for V_* : for example, almost all the mean values shown in Table 22 exceed it. It is approximately equivalent to a wind speed at 300 cm above the ground of $19 \frac{1}{2}$ mph (estimated from the inverse of the relationship in Figure 25: $V_{300} = 0.580 + 28.933 V_*$) and has been exceeded at least momentarily on 65% of the days in the record from the Lindsay Ranch site (Table 25). This record also shows a seasonal variability which matches that found in the earlier analysis of the 1969-1974 record from the Rocky Flats Plant. There is, however, no evidence on the Lindsay Ranch site of sand transport and erosion which this analysis would suggest could occur frequently. This discrepancy is explained by the controlling influence of the vegetation cover and the magnitude of Z_0 . For this reason, V_* does not appear to be critical in defining erosion potential on this site since it is clearly subordinate to the ground surface and vegetation conditions which control Z_0 .

However, it is important to note that this conclusion is site-specific. It cannot be easily extrapolated to other parts of Rocky Flats, or even to a different surface condition on the Lindsay Ranch site itself. It does point to the obvious need to maintain the present vegetation cover in order to minimize wind erosion: a lag gravel on many of the interfluvial surfaces at Rocky Flats suggests past erosion following disturbance of the vegetation.

Summary

Two important points emerge from this examination of the wind records from Lindsay Ranch. Neither can be stated with complete confidence, since they are based on incomplete records of the wind profile, but they are supported by the entire period of record and they do conform to the results gained from other, more complete studies of wind erosion.

Table 25

MONTHLY WIND RECORDS: LINDSAY RANCH

	1975		1976		1977		1978	
	N	n	N	n	N	n	N	n
January			31	24	26	21	25	11
February			19	19	28	21	27	10
March			31	24	31	25	27	12
April			28	20	30	17	28	20
May			31	19	2	0		
June			14	6	N.D.			
July			31	27	N.D.			
August	13	11	17	10	N.D.			
September	30	17	21	6	N.D.			
October	26	13	25	14	N.D.			
November	29	21	24	17	23	14		
December	27	17	28	21	22	19		

N is the number of days in the record

n is the number of days in the record on which wind gusts excess of
19 1/2 mph were recorded.

First, an evaluation of the aerodynamic roughness of the exposed interfluvial site at the Lindsay Ranch suggests that little of the soil in this situation is presently subject to wind erosion, even under winter conditions. This is not surprising given a situation in which the areas of bare soil are usually less than 1/2 m across and are surrounded by a vegetation cover that is up to 30 cm high at all times of the year. The vegetation survey of Rocky Flats (Webber & Clark 1976) suggests that this condition is a common one on most of the exposed pediment remnants of the Rocky Flats surface.

Second, wind shear in the boundary layer is commonly sufficient to entrain sand and finer grains into motion. During the study period, gusts of sufficient velocity to erode particles and aggregates up to 2 mm in size were recorded on more than half the days, with an increased probability of such winds in the winter season. For these winds to be effective in erosion would require modification of the present surface. If that were to occur, winds capable of suspending dust and entraining sand into motion could follow needle ice events by no more than a few days.

CONCLUSION

This report has summarized the results of an empirical study conducted on Rocky Flats to evaluate the potential link between frost action in the soil and wind erosion. Under the undisturbed conditions of the site at which most observations have been made, soil disturbance by frost is much less frequent than might be expected from climatic records of the area. Although more than 100 freeze-thaw cycles occur each winter at Rocky Flats, only about 15 of them lead to surface disturbance through the growth of segregation ice in bare soil. This disparity reflects the need for liquid water in the soil if ice segregation is to occur which is then constrained by the semi-arid environment of the Rocky Flats area. In all cases, the frost and heave cycles recorded in this study have been of short duration (24 hrs) and have affected only the near-surface layers of soil (within 10 cm of the ground surface).

At Rocky Flats, the potential for frost action in the soil is clearly maximized in March, with a secondary maximum in November. At these times 3 necessary conditions combine to produce frost action: alternating freezing and thawing on a diurnal cycle; high soil moisture contents close to the ground surface, and unfrozen sub-surface. The first of these is clearly necessary but, by itself, is not sufficient to cause frost disturbance of the soil. The second acts as basic limit to frost action at Rocky Flats for soil heave only occurs soon after rainfall or snowmelt and is limited by the amount of water so provided. The third is an important restraint on soil frost activity during the mid-winter months, when the soil is frequently frozen to depths of 5 cm or more, and on the valley floors at Rocky Flats. At these times and places, the presence of a frozen layer below the soil surface prevents moisture movement upward toward the freezing plane and so restricts the growth of segregation ice.

The disturbance of the surface soil by segregation ice is clearly evident at Rocky Flats in a qualitative way but has not been satisfactorily defined quantitatively. Lifting of the soil surface by 10 mm is common in heave cycles and up to 40 mm of lifting have been observed on occasion.

Following the ablation of the ice responsible for this, the bulk density of the surface soil may be reduced by as much as 20%, along with a reduction in the soil strength and an increase in its erodibility and roughness. However, it has not been possible to define these changes precisely in this study. Because of the spatial distribution of frost action at Rocky Flats, these effects should be greatest in the soils of the exposed ridges and interfluves, which are also the situations most exposed to wind action.

At the study site near the Lindsay Ranch, wind erosion has not been shown to be effective. This site has an undisturbed surface on which the vegetation cover is a basic aerodynamic control, rather than the soil characteristics. So long as the vegetation remains undisturbed here, and on equivalent sites, there seems to be little potential for soil erosion by the wind. Under these conditions, frost action should not contribute to eolian erosion or to the resuspension of Pu from contaminated soil.

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