Arctic Aeromedical Laboratory

WINTER MICROCLIMATES OF IMPORTANCE TO ALASKAN SMALL MAMMALS AND BIRDS

AAL TECHNICAL REPORT 57-2

LADD AIR FORCE BASE
A L A S K A

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I. INTRODUCTION

One important consequence of the marked increase in human activity in Alaska during the years of World War II and the recent years of the postwar period has been a pronounced and widespread increase in interest in Alaska and in things Alaskan. Hence there has developed a need for information, and a greatly expanded program of research utilizing newly established facilities in previously little explored areas has come into being in Alaska. Thus while the new activity has brought with it many new, or at least intensified, problems it has also brought the means for their solution. Of particular interest are questions of winter survival. For example, what should fliers, and passengers, do to maximize their chances of surviving severe midwinter conditions when aircraft are forced down in the vast wilderness areas of Alaska? And what should residents, and transients, do to survive conditions of emergency in winter such as those that might prevail following the loss of warm shelter by fire or military attack? The research reported here grew out of the new interest and opportunity. It was motivated by a critical need for basic information in the long neglected fields of winter ecology and physiology and to a lesser degree by a need for applications of value in winter emergency survival. It was made possible by the interest and support of the United States Air Force.

Basic Problem

The basic question in this research was: "How do the resident mammals and birds manage to survive the severe arctic and subarctic winter conditions?" An adequate study of this question requires the determination of:

a) what the resident mammals and birds were, b) what they did, c) to what extent they actually survived, d) what the winter conditions were, e) what they did, and f) to what extent they actually were severe. All of these aspects were explored in this research. It soon became evident that the winter conditions were at times exceedingly severe, and that nevertheless a very large number of animals survived them with little apparent difficulty. The research was then organized to investigate some of the principles and procedures applied by the animals which made possible their successful survival. It was hoped that facts might come to light which would be of value to human beings under emergency survival conditions in winter.

The only reasonable way to attack such a complex and comprehensive problem is by means of a team of investigators. The numerous physiological and ecological ramifications of the problem could have been given properly balanced attention only through the services of several or even many investigators and specialists. Meteorological problems are customarily done on a team basis. Yet such a reasonable and practical division of labor was not possible in the case of this research. A research group consisting of four members: Professor D. R. Griffin (project leader), H. T. Hammel, H. M. Johnson, and K. S. Rawson, carried out what research was feasible. D. R. Griffin, H. T. Hammel, and K. S. Rawson investigated several physiological aspects of the problem (20, 22). The author was not able to give much time to any of the many important physiological aspects, instead investigated chiefly physical environmental and ecological aspects of the problem (20, 25). Because of the complexity and scope of the basic problem much of great importance could not be studied in detail.

In an effort to reduce the research to a task of manageable proportions the author confined the major portion of his attention to two special aspects of the basic problem, namely a) the nature of the conditions of the physical environment, and b) animal activity, particularly the gross or behavioral responses of the local mammals and birds to the observed environmental conditions. The environmental studies were largely quantitative, although many useful qualitative results were also obtained. The studies of animal activity were almost entirely qualitative. This limitation resulted from the fact that the activity observations were made in the field under almost totally undisturbed conditions. Also the difficulties of making good field observations were many during the cold, dark, subarctic winters, and time was limited. No attempt was made to determine the mechanisms of the observed responses, nor to analyze fully the dynamic processes of the physical environment. Thus both the geophysical and the biological investigations were primarily descriptive studies.

Previous Studies

Previous studies directly on the basic problem, and on the special aspects of it intensively studied by the author, have been few and to a large extent superficial and speculative. The problem in most of its aspects has been long neglected. Related information, however, on the physical environment (geophysics, geology, climatology, meteorology, and others), and on the associated biology (animal activity, behavior, physiology, winter ecology, mammalogy, ornithology, and others) exists in large amounts and is scattered widely in a vast literature. While scattered bits of information and clues may be found in innumerable, often unlikely, places no one reference sums up the information on any but the most specialized aspects of the total problem. In most of the works examined the relevant information was incidental. Only a few of the most helpful references can be listed here.

The full research program, directed by D. R. Griffin, was an outgrowth of a comparative study of arctic and tropical mammals and birds carried out at Point Barrow, Alaska (and in Panama), by P. F. Scholander and associates. This latter group studied several physiological matters including body insulation, heat regulation, and adaptation to cold in relation to body temperature, insulation, and basal metabolic rates (39, 40, 41). H. T. Hammel of our group, extended the studies of insulation in his intensive study of the role of fur in the physiology of heat regulation in mammals (20, 22). The author's studies were initially motivated by a need for definite information concerning the microclimates to which the arctic and subarctic animals were actually exposed under natural conditions. The previous studies, and almost all of the relevant literature, included virtually no quantitative information regarding these microclimates. What little information was available was seriously incomplete, tended to be misleading or confusing, and often was contradictory. The results of the work of Scholander and associates led to an apparent paradox: How was it that certain species of small mammals could thrive in arctic and still colder subarctic regions even though the insulation provided by their fur was less than that of certain tropical forms? It was felt that a study of microclimates might help to resolve the paradox. Furthermore microclimatic information could also give additional meaning to, and permit a more complete interpretation of, the previous and concurrent physiological studies.

Physiological and ecological problems closely related to the basic problem were then under investigation by a research group directed by

Professor P. R. Morrison at the University of Wisconsin (30); by groups at the Arctic Health Research Center, Anchorage, Alaska; by groups associated with the Arctic Research Laboratory, Point Barrow, Alaska; and by others. Related geophysical studies were being carried out by groups doing research for the United States Army and the United States Air Force, by scientists at the University of Alaska, and by others. Much information, often unpublished, was obtained directly from these active research groups.

Additional useful information was extracted from the extensive literature of several related fields of science. Although numerous references were searched, few provided significant amounts of directly relevant information. Some of the more important of these are listed below.

Fundamental information on snow was obtained from several books (12, 16, 42), from papers such as (19, 26, 27, 32, 38), and from other papers in journals such as the *Transactions of the American Geophysical Union*, and the *Journal of Glaciology*. Important information on soils, permafrost, and phenomena of the frozen ground was obtained from a basic text (31), from a variety of papers including (6, 7, 8, 10, 13, 14, 24, 34, 45, 48), and from other papers in journals such as the *Geographical Review* and the *Journal of Geology*. Fundamental information on microclimatology and micrometeorology was obtained from basic texts (18, 47), from papers such as (44, 50), and from other papers in journals such as (3), and the *Monthly Weather Review*. Important information on animal ecology was obtained from basic texts, notably (1), from a highly relevant paper (17), from popular works such as (23), and from many other books and papers. Valuable information on physiology was obtained from reports such as (30), from texts such as (33, 35), and from many papers, notably (39, 40, 41, 44). Important information on mammalogy was obtained from books such as (2, 9, 21, 29, 43), from papers such as (15, 17, 28, 36, 37, 46), and from many other papers in journals, notably in the Journal of Mammalogy. Information on birds was obtained from works and papers such as (4, 5, 17, 28), and from other papers in journals such as the Auk, and the Condor.

Several of these references merit special comment. Geiger's work on microclimatology (18) contained much of considerable value concerning the nature of microclimates, micrometeorological processes, and the properties of soil, snow, and air, hence was of great value in the development of this research. But it contained little on winter conditions, and virtually nothing on the winter conditions of high-latitude regions. The paper by Wolfe and associates (50) revealed much regarding the practical problems and difficulties of a relatively broad microclimatological field study. It treated winter conditions, but only moderate winter conditions, those to be found in Ohio.

Formozov's work (17) was the most significant paper, being the only one directly on the subject of this research. Unfortunately much of it remained untranslated, because of time limitations, and previous translations, if any, were not located. It contained numerous important winter observations (comparable to those of E. T. Seton (43)) on mammals and birds of the U.S.S.R., but contained little quantitative information on the microclimatic conditions involved. It rightly stressed the importance of the snow-cover.

Alaskan Field Studies.

The field-work phase of this research was carried out in Alaska during two winter periods. The first period of winter research, from January 27 to March 20, 1951, consisted chiefly of preliminary and exploratory investigations. During this period the initial observations of natural, undisturbed, environmental conditions and of animal activity were made, and procedures and instrumentation were developed. The second period of winter research, from December 15, 1951, to March 20, 1952, consisted of an intensive and productive series of routine observations of environmental conditions and associated animal activity, as well as numerous supplementary, often exploratory, observations on special phenomena and on related matters.

Most of the observations were made near Fairbanks, in the continental interior of Alaska. The Biology Laboratory of the Arctic Aeromedical Laboratory, Alaskan Air Command, at Ladd Air Force Base, some three miles east of Fairbanks, served as the base for operations. Most of the field stations were located within a half mile radius from this laboratory, although a few were several miles distant. Additional observations were made at Snag, Yukon Territory, Canada, at Big Delta, College, and Galena, Alaska, in the continental interior; at Nome on the coast of the Bering Sea; at Gambell, St. Lawrence Is., in the Bering Sea; at Barter Island and Point Barrow, on the arctic coast; and at Umiat, inland on the arctic slope.

Continental Alaska consists essentially of an extensive interior plateau, two large roughly east-west mountain ranges, and an arctic slope and coastal plain. The interior plateau, involving about half the total area, and drained chiefly by the Yukon River and its tributaries, is bounded on the south by the massive and lofty Alaska Range and other mountains. It is bounded on the north by the important Brooks Range, a broad, rugged, east-west range with many summits over 7000 feet and some approaching 10,000 feet. Eastward and southeastward the plateau narrows but continues between high mountain ranges and along the Yukon drainage system into the Rocky Mountains of Canada. Westward the plateau widens and drops to the extensive lowlands of the Bering Sea Coast. The plateau is dissected into a system of ridges and low mountains, and large and small basins. North of the Brooks

Range lies the arctic slope, which includes the arctic coastal plain and arctic coast. It consists largely of tundra and tundra ponds to the north and of rolling low hills and foothills to the south, and extends some 150 miles where widest.

Fairbanks (64°51' N, 147°43' W) and Ladd are similarly situated and have essentially the same climate. They are situated on the lowland floor of a large geographical basin, enclosed by mountains and high hills on all sides except for a few narrow channels of the Yukon drainage westward. Both stations are located at an altitude of about 450 feet in the broad flat valley of the Tanana River, a major tributary of the Yukon River. Both are on level slightly elevated land close to the Chena River, a relatively narrow tributary of the broad Tanana River. The Tanana flows westward about 4 miles to the south. Hills some 800 to 1000 feet in altitude rise abruptly from the lowlands about one mile north of the Ladd station, and similar hills are found a short distance north of Fairbanks. Hills with altitudes over 1000 feet, and some over 2000 feet, are found in the increasingly hilly areas northward. Northward these become the White Mountains, which lie about 50 miles to the north and northeast and include a few summits over 5000 feet. Similar hills rise from the lowlands about 25 miles to the east and become mountains about 60 miles to the east and about 40 miles to the east-northeast. Similar hills rise from the lowlands a short distance westward, but these terminate at an extensive area of lowlands at a distance of about 30 miles. Southward the relatively flat lowlands extend some 50 miles to the foothills of the extensive and high Alaska Range, which rises to 13,740 feet at Mt. Hayes some 85 miles south-southeastward, and to 20,300 feet at Mt. McKinley some 150 miles southwestward. Also southwestward the lowlands join with the extensive lowland areas which lie to the west. These lowlands together form the floor of the large geographical basin.

This basin is one of several important large basins which together with adjoining hills, low mountains, smaller basins, other lowland areas, and drainage systems comprise the Central Alaskan Plateau region. North of the White Mountains and forming the northeast portion of the plateau is another, larger basin. Near the center of the basin, some 140 miles north-northeastward from Fairbanks, about 1.5 miles north of the Arctic Circle, and at the confluence of the Yukon River and the Porcupine River (a major tributary) lies Fort Yukon. Across a range of high hills west of this basin is another, much smaller, basin with a similar climate. These basins are notable for having the Alaskan climates most strongly affected by sub-arctic continental influences, hence averaging coldest in midwinter. The subarctic winter conditions near Fairbanks are similar but tend to be less highly developed. Maritime influences affect the eastern three-quarters of the plateau relatively little in winter, are minimal over the eastern and northeastern sections of the plateau, but become pronounced over the far western and southwestern sections. They form an important component of the climate of the large basin within which Fairbanks lies.

The other stations visited in the continental interior were situated as follows: Snag, about 283 miles southeast of Fairbanks, on the White River (an important north-flowing tributary of the Yukon), in a small basin surrounded by high mountains (particularly nearby to the south) and high hills; Big Delta, about 74 miles southeast of Fairbanks, at the junction of the Tanana and Delta Rivers, and in a basin-like valley; College, about 2 miles northwest of Fairbanks; and Galena, about 270 miles west of Fairbanks, and on the Yukon. Nome lies about 530 miles west of Fairbanks, nearly at sea level on the coast of the Bering Sea.

Point Barrow is situated on the coast of the Arctic Ocean, a few feet above sea level, about 500 miles north-northwest of Fairbanks, about 330 miles north of the Arctic Circle, and at the northernmost point of land in Alaska. From southwestward through northward to east-southeastward lies the Arctic Ocean, the Chukchi Sea to the west, the Beaufort Sea to the east, ice covered most of the year. Southward the Arctic Coastal Plain and the Arctic Slope extend some 150 miles to the foothills of the Brooks Range. This plain of tundra narrows both westward and eastward as the coast approaches the Brooks Range. It is drained by several sluggish north-flowing rivers, the largest being the Colville River which enters the ocean about 150 miles east-southeast of Point Barrow. Lakes and other shallow bodies of water are exceedingly numerous on the northern half of the plain. Barter Island lies about 300 miles east-southeast of Point Barrow, at the eastern narrow portion of the plain, just off the coast in the Beaufort Sea. The station is nearly at sea level.

Umiat lies inland about 170 miles roughly southeast of Point Barrow, at an altitude of about 350 feet, on the Colville River about 85 miles south of the Arctic Ocean, and in low hilly country just north of the foothills of the Brooks Range.

The climate at Point Barrow averages colder even during the coldest months and remains cold longer than the climate at Fairbanks, but does not reach such extremes of cold (see table I). The conditions tend to be colder eastward along the coast. This coldness reaches its extremes in northern Canada and the Canadian Arctic Archipelago. The conditions also average colder, in midwinter, in the colder portions of the continental interior.

TABLE I

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Annual
Point Barrow													
Mean Temperature	40.0	38.5	31.0	16.6	0.0	-11.7	-16.7	-16.9	-14.8	- 0.2	19.5	34.7	10.0
Mean Maximum Temp.	46.7	44.0	35.0	21.8	5.8	-5.2	-10.5	-10.6	- 7.4	7.6	25.3	40.0	16.0
Mean Minimum Temp.	33.7	33.1	27.0	11.7	-6.3	-18.0	-23.3	-23.8	-22.0	- 7.5	13.6	29.4	4.0
Absolute Minimum Temp.	22	20	4	-25	-43	-55	-52	-56	-52	-42	-18	8	-56
Fairbanks													
Mean Temperature	60.0	55.1	43.6	26.6	3.4	- 7.1	-11.3	- 1.2	9.6	29.4	46.9	58.4	26.1
Mean Maximum Temp.	70.7	64.1	53.5	34.8	11.5	- 0.2	- 1.7	4.9	22.2	42.5	58.1	69.8	35.8
Mean Minimum Temp.	48.4	43.9	34.4	20.1	- 4.2	-16.1	-20.6	-17.3	- 6.2	19.9	34.9	46.1	15.2
Absolute Minimum Temp.	34	28	12	-28	-38	-59	-66	-54	-44	-25	4	32	-66

(data from USAF)

Thus in general the midwinter temperature conditions on the Arctic Coast of Alaska are more moderate than those of the interior. This difference is due to the moderating influence of the Arctic Ocean.

Sources of Information

To increase the efficiency of the research and to allow full utilization of any existing relevant information an attempt was made to use many sources of information. Actually the complexity and vastness of the basic problem, and also of the special aspects of the problem selected for intensive study, made this procedure quite necessary. Even the special problems involved many factors, many variables, and many phenomena. Although many of these had been well studied, others had been long neglected, and very likely still others had been overlooked entirely. During the early exploratory phase of the work, to avoid neglect of factors of unsuspected importance, all available sources of information of possible value were sought out and utilized. During the later intensive phase of the work, after the relative importance of the various factors and the fruitfulness of the various sources had been evaluated, emphasis was given to a selected few variables, phenomena, and sources of information on these, although exploratory work was continued. Some important factors did remain little studied, however, because of limitations of time, equipment, and facilities.

Useful information representing the work of others was obtained from several sources: 1) It was sought in the literature, especially in books and papers on geophysics, meteorology, ecology, physiology, mammalogy, ornithology, and exploration. The literature provided much useful background information, but contained almost nothing specifically on the basic problem or the special aspects of it studied in this work. 2) It was sought from local sources including: a) weather stations of the 11th Weather

Squadron of the United States Air Force, and of the Civil Aeronautics Administration, and other weather stations, which provided essential current meteorological information; b) the University of Alaska - staff, collections, and library; c) local biologists and trappers, who provided information on current distribution, abundance, and activity of animals; d) and local Air Force personnel in the field for reasons of tests, training, and work, who brought in specimens and reports on activity. 3) It was sought in consultations with scientists interested in Alaskan and arctic and subarctic problems. Since much of the related research was recent, and largely unpublished, these consultations proved very informative and helpful. P. F. Scholander, P. R. Morrison and associates, scientists at the Arctic Health Research Center, Anchorage, at Ladd Air Force Base, at the Arctic Research Laboratory, Point Barrow, and scientists attending the Second Alaskan Science Conference were especially helpful.

Useful information representing the work of the author was obtained in the field by means of exploratory observations at nearby habitats, intensive routine observations at the same habitats, exploratory observations at more distant local habitats, and essentially exploratory observations at habitats in other regions. Most of these observations were made during the winter, although some were made in the fall (Fairbanks, 1951). Other incidental observations were made in the spring and summer (Fairbanks, Pt. Barrow, 1947) and in the fall (Fairbanks, Pt. Barrow, 1947; McKinley Park, 1951.)

The results of this research, the final information, were derived from and composed of two quite different types of data, both very important. Numerical data were successfully obtained for: a) temperatures of the soil, snow-cover, and air, b) wind velocity, air drift, and drainage air motions,

c) cloud extent, distribution, altitude, and motion, d) snowfall times, rates, and depths, e) snow-cover depth, density, settling, and evaporation, f) humidity, g) pressure, h) positions and times, and i) some types of animal activity (such as times of activity, numbers of individuals involved, and relative density of snow holes and surface tracks). Some of these quantitative data were important, abundant, and largely adequate (temperatures); some were important, abundant, and inadequate (temperatures, cloud conditions); some were important but few and inadequate (wind conditions, animal activity data); and some were of lesser importance (humidity, pressure). Some important quantitative data could not be obtained with the equipment available (notably data on radiation conditions). Much information was extracted from these data plotted in comparative graphical form. Tables were of little value. But because of time limitations and the formidable difficulties of a fully detailed analysis much information remains unextracted, and much data that has been analyzed cannot be presented in quantitative form here.

Equally important were the qualitative, descriptive, geophysical, and biological observations. Observational data were obtained for: a) temperatures of the soil, snow-cover, and air, and details of temperature structure, b) wind velocity, air drift, drainage, and details of the structure of these air motions, c) cloud type, structure, extent, distribution, altitude, and motion, d) snowfall conditions: type of fall, type of snow, times, rates, and depths, e) ice fog, ice crystal, water fog, rime, and frost conditions, f) snow-cover conditions: type of snow, internal structure, type of metamorphosis, settling rates and extent, distribution, depth, density, and disturbance, g) radiation conditions, h) humidity conditions, i) soil conditions, j) topography, k) positions and times, l) vegetation: type, distribution, abundance, condition, and association, m) animals: type, distribution, abundance, condition, survival, activity patterns, behavior, and other matters, and n) special phenomena: type, occurrence, factors affecting and processes causing, influence upon other phenomena, and other matters. The special phenomena studies included: the subnivean air spaces, the flow of air into and out of the subnivean zones, cold pockets, warm "pockets", cold air drainage, ice fog, permafrost phenomena, topographical effects, and others. Data of this type provided much of the desired and needed information. While it was often scanty or inadequate, and tended to lead centrifugally into new areas of research, it was at other times quite adequate for the purposes of this research, and was usually informative and rewarding. Without the qualitative data much if not most of the significance of the quantitative data would be lost. Conversely, the quantitative data give significance to the qualitative observations.

Energy Approach

The problem of survival of mammals and birds (homoiotherms) under arctic and subarctic winter conditions is fundamentally a problem of energy exchange and balance. Energy must be gained and conserved in amounts sufficient to counterbalance the high losses that result from, and are a measure of the severity of, the severe environmental conditions. A proper investigation of the basic problem, and many of its special aspects, should include a quantitative determination of the energy budget of selected environmental zones through selected periods of time, and of the energy budget of individual animals moving through such zones at such times. While such determinations might be made to a good degree of approximation with currently available techniques, the measurements required are sufficiently difficult, and the details requiring attention are so numerous, that such determinations rapidly reach unmanageable proportions, hence become prohibitively difficult for all but the largest or best equipped research groups. In this limited research program it was not practical, nor often possible (because of inadequate time, instruments, and facilities), to make quantitative energy determinations, despite their fundamental importance. In some cases environmental rates of energy gain and loss could be approximately calculated, as from snow and soil temperature data. Few such calculations were completed, because of time and other limitations. In his research, H. T. Hammel determined local rates of heat loss through the fur of living animals (22). While such spot measurements are helpful they are still far from an integrated energy budget, even one for a very short period of time.

Lacking a quantitative picture of energy relationships, much information still can be derived from qualitative data. From an energy point of view the basic question can be rephrased: "How do the resident arctic and subarctic mammals and birds manage to gain enough energy, store enough energy, and reduce energy losses sufficiently to permit survival of the most severe winter conditions?" An answer to this question requires a determination of: a) sources of energy (from what sources may and do animals gain energy?), b) sinks of energy (to what sinks may and do animals lose energy?), and c) means of energy transfer (through what channels or processes may and do animals gain or lose energy, or control rates of energy exchange?).

Energy sources are few in midwinter. They include all materials warmer than the animals or than parts of the animals, notably: the sun, warm soil, other animals, human habitations, sunlit materials, and clouds. Rarer sources, such as hot springs and other evidence of volcanism might be included.

They also include materials that may not be warm, notably food materials. Energy sinks are numerous and widespread in midwinter. They include all materials colder than the animals, notably: the clear night sky; cold surfaces as of vegetation, soil, and especially the upper surface of the snow; and cold materials as air, snow, soil, rocks, metals. They also include other types, such as cold food and water materials, droppings, exhalations, and evaporation.

The means of energy transfer are chiefly and basically five: 1) transfer by true conduction, 2) turbulent transfer (convection) and other mass transfer, 3) transfer by radiation exchange, 4) change-of-state transfer (as in evaporation), and 5) transfer through chemical (and metabolic) change. Under natural conditions the first four processes usually occur in combination. Energy losses by conduction and convection, and by radiation exchange, are often of the greatest importance. However, all of these means of energy transfer may be at times of considerable importance. Control by the animals of their losses is achieved chiefly by means of insulation (physical and physiological insulation, affecting conduction and also convection and radiation losses), and by means of microclimate selection (involving conduction, convection, and radiation losses primarily), but also is achieved by means of other physiological and behavioral adaptations. Control of energy supply is achieved through habitat selection (selection of food sources, on the basis of amount available and type of food), behavior (harvesting, storage....) and many morphological, physiological, and other adaptations.

A continuous effort was made during the field research and during the analysis and reduction of the data to keep energy considerations in mind, to determine the sources and sinks, and to evaluate the importance of these and of the various means of energy transfer, in the different microclimatic zones and during times of different environmental conditions. As a consequence some information on energy was gained, but almost all of it was of limited quality, representing simple qualitative observations and interpretations. So far as this research is concerned the energy considerations remain in a primitive, approximate-descriptive stage. A more precise description, and a full treatment of the dynamics, await advanced future research. Furthermore many answers to aspects of the basic problem depend on quantitative applications of the energy approach; thus many important advances can be expected to follow the further development of this promising and natural approach.

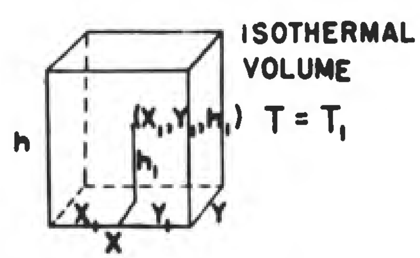
Descriptive Approach

The work of the research fell into three main categories: 1) instrumentation and operations, 2) description of the microclimates, and 3) investigation of animal activity and response to the environmental conditions. In the instrumentation and operations phase of the work, which consumed much time and energy particularly during the early stages of the research, many operational difficulties were overcome, and equipment and procedures were developed. This phase will be discussed briefly in section II below. The second phase, description of the microclimates, is the chief concern of this paper. In it an approach was developed, which though quite natural, in fact almost obvious, was one of the more important achievements of the research. The approach will be briefly outlined here; later, in section III, selected examples of results obtained using the approach will be presented. While adequate descriptions of the microclimates must precede investigations of animal response to the microclimatic conditions, and therefore a great deal of time and energy was expended in an effort to achieve such descriptions, the study of animal activity and response to the microclimatic conditions was actually the primary objective of the research. Although most of the field-work was devoted to this phase, the many, often extreme difficulties were not fully overcome so that the results of this phase remain preliminary and relatively incomplete. This work will be discussed briefly in sections III and IV below.

To achieve an adequate description of a microclimate one must first answer the questions: 1) what is a description (a precise description; an approximate description of minimal adequacy)? 2) how is one obtained? 3) how is one expressed or represented? The answers to these questions are not as easy to obtain as is generally supposed.

In this research the conditions of the physical environment were thought of in terms of physical <u>fields</u> of certain variables. By way of illustration let us consider a simple case consisting of a) temperature conditions only, with b) time changes small or absent. Consider a volume of material (see sketch A). In this three numbers (coordinates) suffice to specify precisely the position of any point: two numbers, x and y, determine the horizontal position, and a third, h, gives the altitude. In this volume the temperature conditions form a temperature field. The field is precisely described by specifying for every point the temperature at that point. Thus for each point four numbers (coordinates) are required, (x, y, h, T), three to give the position, and another, T, to give the temperature.

A)



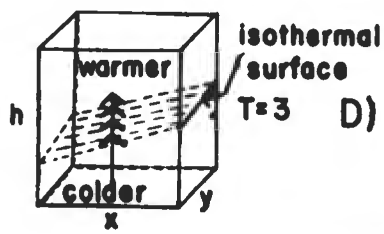
B)

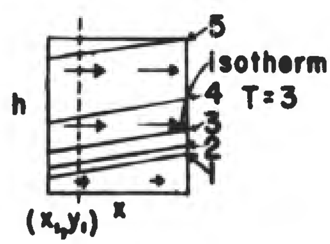
Of course in any volume there is an infinite number of points, but this does not mean that every precise description requires an infinite number of specifications. Consider the case where within a volume all of the temperatures are the same, or T equals T_1 everywhere. In this, the rather common special case of an isothermal temperature field, a precise description consists of a statement that the field is isothermal, and that the temperature is T_1. Of course the position of the field must be stated as well. These remarks are strictly true only if the temperature field does not change with time. If the isothermal field changes slowly with time, and remains isothermal at all times, a precise description requires the inclusion of a full description of the time changes at any one point. This latter description can be closely approximated by means of a graph of the time series giving the temperatures at a point through a period of time (see sketch B). When the field is known to be isothermal the conditions can be fully determined by the use of one continuously registering thermal element (such as a properly exposed thermometer, thermistor, or thermocouple), but this is the only case in which one thermal element is adequate. In practice, more thermal elements would be required, to provide the information that the field was isothermal, and to check instrumental accuracy.

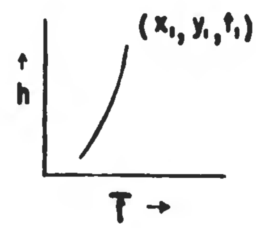
When fields change with time it is necessary, in the general case, to specify five coordinates, (x, y, h, T, t), four as before, and another, t, to give the instant of time. Thus, in a precise description, the values in each such set of five numbers must be specified for every point not for just one moment of time but for every moment of time (in each period of time under consideration). In a few simple cases this full information can be compactly stated in the form of mathematical expressions. In all other cases a precise description is impractical or virtually impossible. In these cases it is necessary to use empirical, approximate descriptions, the degree of approximation necessary or adequate depending upon the purposes of the investigation.

Let us now consider another common special case, that of a simple, stable, stratified temperature field. In a volume of material the temperature conditions, whether precisely or approximately known, can be approximately represented by means of isothermal surfaces (which may be thickened locally into isothermal volumes) (see sketch C). In the sketch, to avoid clutter and confusion, only one isothermal surface is represented. The temperature of the surface is taken to be 3 (arbitrary units). A tree is included to suggest a possible scale. This is the best type of representation, for it permits the clearest visualization of the temperature conditions. With it the conditions may be visualized as a set or series of isothermal surfaces which in general tend to change in shape and position with time. It has limitations: 1) not many isothermal surfaces can actually be drawn because additional surfaces quickly clutter the picture, so 2) with it only a rough approximation can be attained, and 3) small details tend to be obscured or lost, and 4) time changes can be represented only crudely by means of a sequence of such diagrams (which though good for slow changes are quite inadequate for rapid changes).

To permit more detailed study a section of the field, or a side of the volume as sketched in sketch C, may be represented as in sketch D. In this the intersections of isothermal surfaces with the plane of the section form isothermal lines or isotherms. Several isotherms are sketched in to represent typical temperature structure, and are labeled (in arbitrary units).

C)


D)


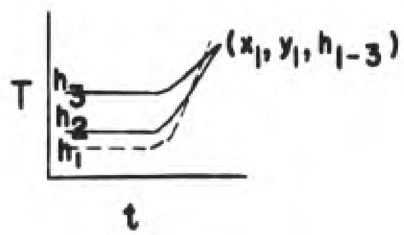
E)


Similar representations might be made for the other five sides of the volume of sketch C. Or the temperature conditions for the moment could be represented approximately by a series of parallel sections, such as a series parallel to sketch D and extending along the y axis. Such serial-section diagrams are not often constructed, because of the labor involved. A type of representation easier to make, and commonly made, is the temperature profile. This is a graph of the temperatures found at different heights along a vertical line (such as the dashed line in sketch D) plotted against height (see sketch E). For each such 2-dimensional plot three coordinates are fixed, (x_1, y_1, t_1). A family of such curves, as for successive points along the x axis, is required to reconstruct a representation of the type shown in sketch D, a more informative 3-dimensional type. A family of profiles for successive moments of time, plotted together, form a useful 3-dimensional representation. The same type of information may be expressed in more detail and more clearly by means of a family of time series, also a 3-dimensional type of representation, (see sketch F). However, none of these representations is, in general, adequate to express more than a small fragment of the whole picture of the temperature conditions, for that whole is 5-dimensional. Yet it is the whole, the changing temperature field, the 5-dimensional phenomenon, which is reality, and which therefore is actually under examination. It is of the greatest importance to remember that these diagrams, 2-dimensional or 3-dimensional, and convenient as they are to study, are only small pieces of evidence from which the whole picture, that of a changing temperature field, must be pieced together and visualized. The best aids that can be drawn on paper, diagrams of the type shown in sketch B, which are approximate but 4-dimensional, and series of them, which are crudely 5-dimensional, leave much to be desired.

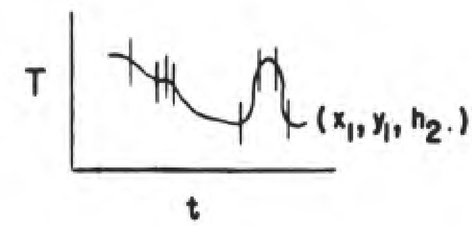
Yet they must be used, and usually must be reconstructed, at least mentally, from 2- or 3-dimensional plots such as those shown in sketches D to F. This was done throughout the research; thus both the procedures and the results of the research are based upon this step and this approach. Therefore it is necessary for the reader to attempt similar reconstructions and visualizations in order to understand and interpret the procedures and results of this research.

Large or rapid changes in conditions are best represented by time series curves, and plots of families of time series. A time series representing such changes is suggested in sketch G. In this sketch the temperature variation might be 50°F, and the time span several days. In such plots the spatial coordinates are fixed, (x_1, y_1, h_2).

F)



G)



In this research the changes were thought of in terms of events, events which occur at a point and may occur throughout a volume. An event may be of a state of the environment, or a sequence of such states. Thus the conditions at each instant may be taken as separate events, or a long sequence of such events may be taken as an event. In this research the events considered were usually relatively short sequences, and major and minor events (of primary, secondary, and lesser degree) were distinguished. A major event, a term used loosely, was taken to be an event: a) of appreciable duration, b) clearly distinguishable from preceding and following conditions, c) representing a major type of weather state or environmental situation, or representing a major component of the pattern of conditions, d) usually representing one type of situation, and e) representing a system of environmental conditions that might well be, or was known to be, distinguished by and of importance to the resident mammals and birds. The major events of sketch G might be marked off as by the red lines. Examples of such events include: periods of continuous low and relatively constant temperature, periods of a single type of rapid temperature rise or fall, continuous warm periods of a single type, and many others. In some cases, such as those of storms and cold-snaps, it was convenient to consider a sequence of such major events as another type of major event. The remaining events are the minor events.

It is to such events, major and minor, not to conventional average conditions, that plants and animals are exposed and respond. Thus the climates to which living things respond are nothing more than sequences of such events, major events linked by minor events, slightly to greatly different from year to year and from place to place. Ordinary climates or macroclimates are supposed to represent air-mass conditions, conditions little affected by local surface influences. These are the conditions which standard instruments in standard weather shelters are supposed to determine with acceptable accuracy. On the other hand microclimates are the climates of the zones strongly affected by surface influences. Clearly, standard station data will not normally provide much information on microclimates. The sequence of events which are the microclimates: 1) grade into the macroclimate upward (forming an intermediate zone of transitional conditions which is sometimes called the zone of mesoclimates), 2) cannot be of arbitrarily short duration (for a climate must have appreciable duration), and 3) are, strictly speaking, infinite in number. To avoid using the word "microclimate" for what is really many microclimates, and for conditions of short duration, the term "microclimatic conditions" is used instead in this research. Microclimatic conditions are the conditions in spaces or materials in the zones of microclimates or zones strongly affected by local influences. They may refer to one moment of time, a sequence of moments, a minor event, a major event, or any sequence of events. They are the usual physical environmental conditions of plants and animals.

Conventional standard stations are one-point stations. While data obtained at one point alone may be adequate when representative of air-mass conditions, which are usually relatively uniform over large distances, they tell little or nothing of the structure of the fields and distributions of the microclimatic conditions. To determine these conditions in a given volume of materials, in general, measurements at many points must be made. The points should be sufficient in number to permit determination of the main features of the fields and of such lesser details as may be important or of interest. But it is usually quite impractical to use more than the minimum number of strategically located points required for an adequate approximate description. This number depends upon the complexity of the most complex event to be described and upon the degree of approximation desired. In this research over 80 points, of varying importance, were used regularly in the determination of temperature conditions. This number gave a good degree of approximation most of the time, because of the inherent simplicity of the arctic and subarctic winter conditions.

In addition to the temperature fields, with their structure and patterns of change, distributions of the values of other variables must also be considered. Most of these are also best thought of as the fields that they are in reality. They too show changes that occur as events. Furthermore they are subject to the same difficulties of representation; and each variable adds one to three new coordinates to the total picture of the physical environmental conditions. Winds, which are very important components of the total conditions, form vector fields. For a vector field it is necessary to specify not only a magnitude at each point and time but also the direction associated with the magnitude. This requires three coordinates, such as (W_x, W_y, W_h), the components of the wind in the x-direction, the y-direction, and the h-direction respectively. Such a field can be visualized approximately by sketching a few arrows (of proper length to indicate wind speed or magnitude and of proper orientation to indicate direction) into diagrams of the type of sketch C or sketch D (see sketch D). Thus one must visualize superimposed fields of variables, in fact, superposed changing fields of variables. This was done throughout this research. Distributions such as those of water vapor, d_w, air density, d_d, and other variables, d_1, d_2, ..., form scalar fields (as did temperature), each adding one more coordinate. Some variables, such as those constituting the radiation conditions, are not so conveniently considered in terms of spatial fields as in terms of distributions about the total surface effectively surrounding a given volume or object such as an animal. These may be visualized best as changing surface distributions. Since the conditions are many-dimensional, requiring specification of values of sets of many coordinates $(x, y, h, T, W_x, W_y, W_h, d_w, d_d, d_1, d_2, \ldots, t)$ for every point and every instant for a precise description, and for many strategically located points for an adequate approximate description, the twin tasks of determination of conditions and of representing the information once determined both become exceedingly formidable if not virtually insurmountable. While a few measurements usually fail to provide the required information and many easily provide overwhelming amounts of information an intermediate number for selected situations, a number based upon major details and planned omission of other details, may prove manageable and practical and provide an adequate approximate description.

Thus the description of the complex natural conditions through which animals move is a challenging and difficult problem. An approximate description omitting variables of lesser importance, covering only the major features of structure and change, visualized as a system of superimposed changing fields surrounded by surface-like distributions of radiational influences, and utilizing short-period averages when necessary to eliminate minor turbulent fluctuation, may prove both practical and adequate. Such a description, based on the reality of fields and other distributions, and based upon meaningful approximations, was attempted in this research. A selected few details, particularly on temperature conditions, the most important and most adequately measured conditions, are presented as the main part of the quantitative results which can be included in this paper.

Description of Habitats

The area most intensively studied, that part of the continental interior which lay within a two-mile radius of the AAL Biology Laboratory, included several types of terrain and a number of habitat types. Most of the area was valley lowland. A predominantly east-west river, the Chena River, meandered through the lowlands and passed near the laboratory. Some of the south slope and summit areas of an east-west ridge, locally known as Birch Hill, were also included in the area.

The laboratory was situated south of the river, on a tongue of lowland around which curved a loop of the river. The river lay about 400 feet to the west, 600 feet to the north, and 1000 feet to the east. This ice and snow covered river formed in effect a flat-bottomed channel some 200 to 500 feet wide and cut some 10 to 20 feet into the valley lowland. North of the river was a rather extensive area of relatively wild lowland. About 4000 feet north of the laboratory this lowland area terminated abruptly at the base of Birch Hill. Within another 2000 feet northward the ridge rose about 500 feet. A road led northward from near the laboratory, crossed the river on the ice, crossed an east-west road near the north bank of the river, extended northward over the valley lowland crossing the Chena Trail (an important east-west dogsled trail) a little less than halfway across this lowland area, crossed another roughly east-west road that ran along the base of Birch Hill, and joined with a road that led diagonally upward and eastward to join with a road along the top of the ridge.

A few habitats in the area were intensively studied, others were studied routinely but not intensively, and many others were studied only exploratorily. The habitat areas most studied include the following:

1) Bar. In the river channel, near the north bank along the north side of the loop, and about 1000 feet from the laboratory was a willow-covered river bar. This roughly east-west bar was about 50 to 100 feet wide, about 1000 feet long, and rose several feet above the river level. North of the bar, between it and the north bank of the river, was a narrow, shallow channel and a relatively wide, grassy, low area. Shrubs grew along the north bank, and similar shrubs, small deciduous trees, and a few spruce trees grew along the top of the bank. Snowshoe hares (Lepus americanus) frequented the willow area of the bar and traveled from there on a limited number of runways to the river bank, bank top, and valley lowland area northward. Voles (Microtus oeconomus) occurred in some abundance in

the subnivean zones of the wide grassy low area. They and shrews (Sorex cinereus) also occurred at other, usually grassy, areas elsewhere on the bar and to a lesser extent near the margins of and in the willow thickets. Small birds, including redpolls (Acanthis sp.) and chickadees (Parus atricapillus), fed in and under the shrubs of the river bank and occasionally in the willows. The snow-cover remained deep and undisturbed in this area (except for some minor unavoidable disturbance resulting from human activity). The atmospheric microclimates tended to be unusually cold in this area, especially on the northern side of the bar.

2) Small Depression. South of the laboratory, about 500 feet distant, was a small depression or basin, part of a small roughly east-west channel that probably once crossed the tongue of lowland. This depression, where deepest, was about 20 to 30 feet wide, about 50 feet long, and cut 8 to 10 feet into the tongue of lowland; (it was over 100 feet long as a two-basined relatively deep channel and over 300 feet long as a significant channel.) Shrubs and small deciduous trees (mainly birches and alders) grew on both banks of the channel and formed a small woods to the north. A rank growth of grass and sedges covered the floor of the basin (see fig. 2, for fall 1951). In winter some ice was present at the lowest level. Microtus occurred in the subnivean zone of the grassy area and of adjacent areas along the adjoining slopes. Small birds fed extensively on the shrubs along the banks. The snow-cover remained deep and undisturbed (except for a narrow observation path)(See fig. 1 for winter 1951-1952). The atmospheric microclimates were unusually cold in this depression.

3) West Bank Area. The area directly across the river westward from the laboratory and about 600 to 900 feet distant, consisting of the river bank, the bank top, and the adjacent valley lowland, included several

FIGURE 1

FIGURE 2

habitat areas of interest. Shrubs grew along the roughly north-south river bank; and similar shrubs, small deciduous trees, and a few spruce trees grew along the bank top. On the valley lowlands open areas, dense and open shrubby areas, dense spruce groves, and open tamarack stands all occurred within the study area. The study area extended along the river for some 1500 feet, was about 100 to 200 feet wide to the south, and widened to over 500 feet to the north. Red squirrels (Tamiasciurus hudsonicus) lived in the spruce groves. Red-backed mice (Clethrionomys rutilus) lived in the subnivean zones of the shrubby and lightly wooded areas along the bank top and of the open tamarack stands in the northwestern sector. Snowshoe hares also utilized the area to some extent. Some small birds fed extensively in the shrubs, while others fed in the conifers. Large birds, such as ravens (Corvus corax) and grouse (Pedioecetes phasianellus), also fed and roosted in the area. The snow-cover of this more exposed valley lowland tended to be less deep than that of the lower areas and more disturbed by winds. Here the atmospheric microclimates were cold, but were significantly more moderate than those of the adjacent low areas.

4) Laboratory Area. The area adjacent to the laboratory included several habitats of interest. Several species of small birds fed or roosted in the groves of poplars, small deciduous trees, and shrubs that enclosed three sides of an open area about the laboratory. On the east and west the nearest groves were about 50 feet from the laboratory, while on the south dense vegetation began at a distance of roughly 200 feet. Other animals were also in the area. Weasels (Mustela erminea, and possibly also M. rixosa) hunted in the area. The animals in the outdoor cages of the laboratory, and the sled dogs, were in the area. The instrument test station and standard weather shelter station were in the area immediately west of the

laboratory. The snow-cover and atmospheric microclimatic conditions were similar to those of the West Bank Area. The Laboratory Area, however, was considerable more affected by disturbance due to human activity. The chief consequences were 1) a scarcity of wild small mammals, 2) a disturbed snow-cover in all but a few protected areas, hence 3) a disturbed thermal regime in the soil of much of the area, and 4) atypical low soil temperatures.

5) Birch Hill Squirrel Area. High on the south slope of Birch Hill, about 400 feet above the valley lowlands, and about 1.5 miles northeast of the laboratory (but over 2 miles distant by road) was a dense stand of spruce in which a group of red squirrels lived. Other small mammals and birds, large and small, were active or lived in or near the spruce stand. The squirrels, however, were the animals of greatest interest. Under openings of this area the snow-cover lay deep and undisturbed, while under dense spruce canopy the snow-cover was appreciably altered by interception of snow by trees and by chunks of snow falling from trees, and was only about half as deep. Winds affected this area more than they affected the lowland areas, but did not directly affect the snow-cover much, largely because of the protection provided by the trees. The atmospheric microclimates of this area were the least cold of those studied.

6) Other Areas. Many other areas within this general area were studied to a lesser extent. About 250 feet southeast of the small depression was another larger, east-west depression some 80 feet wide, 300 feet long, and 15 to 20 feet deep. Conditions in it were studied during the first winter period, but because of scarcity of animals in the area were given little attention after that. The river bottom, the east bank area west of the laboratory, the terraces of the northern and eastern portions of the tongue of lowland, the lowland area north of the river, the areas adjacent to the

Chena Trail, areas along the base of Birch Hill, and areas on, and in the gullies of, the south slope of Birch Hill were all studied repeatedly. Numerous other areas were studied only once or were briefly explored. Areas in other regions, such as those on the Arctic Slope, will be described when they are discussed in sections III and IV.

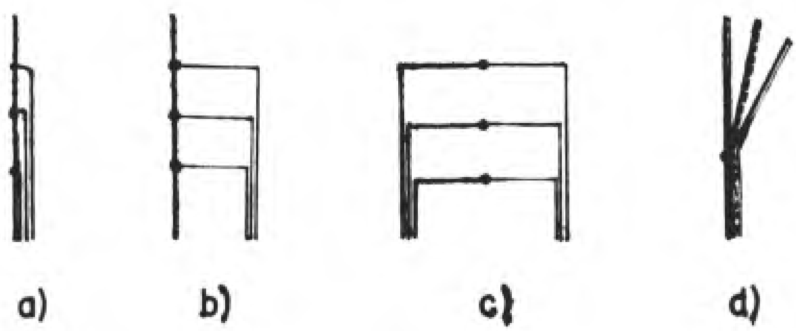
II. METHODS AND APPARATUS

Instruments

The instruments utilized in this research represented a variety of types and a wide variation in adequacy and usefulness. Because of the severely cold and difficult field conditions, because of the fact that most commercially available instruments were developed for use in more temperate climates, and because of previous experience with unpredictable local operational difficulties, some unavoidable failure of instruments was expected. To reduce the loss of data that might result from the failure of the more adequate, usually more expensive, types simple inexpensive alternate types were obtained. Still other types were procured for testing. Use was also made of standard weather, shelter instruments and other instruments belonging to other organizations.

Thermometric instruments. Since temperature was early seen to be the most important variable, it was the variable most intensively studied and most adequately measured. For the accuracy required in the detailed determination of local temperature fields the thermometric instruments available were both very useful and fairly adequate. The best instrument was a Brown recording potentiometer (model 153X64P16-W7-41). It ran through a cycle of 16 points every 4 minutes, and was run continuously in the laboratory during the second winter period. Another (model 153X64P16-W6-41) was used as an alternate. Multiple leads ran from the recorder to a system of copper-constantan thermocouples. Plugs and switches at the recorder and at the field stations permitted the selection, singly or in sets, of any of some 80 thermocouples. Short leads ran to additional test and calibration thermocouples in the laboratory, while long leads of various lengths ran to the microclimatic stations. All leads but the longest were of Leeds and Northrup thermocouple wire (1938 calibration, mostly No. 16 and No. 30 B&S Ga.). The longest leads were of insulated, ten-conductor, No. 24 B&S Ga., copper wire. These were strung both overhead and along the ground surface underneath or within the snow-cover. The first case permitted some erroneous fluctuation at the recorder due to variations in wire tension (caused by occasional winds or human activity), while the second permitted some disturbance and loss of record (caused by human activity). The constantan branch consisted either of individual wires to each thermocouple, of a common wire, or of a combination of these arrangements. To reduce resistance in the long leads a copper wire was substituted for the constantan branch. Ice baths, one in the laboratory (requiring renewal once each day) and one at each field station (requiring renewal every other day), were used to keep both ends of the copper substitute wire at the same temperature, and also provided a known calibration check temperature. With this procedure errors due to resistance were negligible for leads 500 or even 1000 feet in length. Resistance, however, did impose a limit on the useful length of leads.

The thermocouples used were almost entirely of one type. This most useful type consisted of a simple junction of No. 30 copper and constantan wires, the junction formed of freshly scraped wires closely applied by several turns of the copper wire and protected by a minimum amount of rosin-core solder. When tested the thermocouples proved to be essentially identical. No differences were detected when measurements were made to an accuracy of about 0.05°F. Similar unprotected thermocouples, and other types including butt-joined thermocouples, were used in a few special situations. The thermocouples were used singly, in clusters connected to a common constantan wire, or in sets of up to 30 on a common constantan wire. The type of cluster or set used depended on the type of temperature field to be measured. Where gradients were relatively small thermocouples were spaced widely, as one or even ten feet apart, and were on a straight constantan wire with each copper branch leaving laterally (see sketch a). Where vertical gradient components were large and lateral gradient components were small (a very common situation) error due to heat conduction along wires was reduced by use of ladder-like arrangements. In one of these (sketch b), from each thermocouple the copper wire extended laterally for a few inches, approximately along an isothermal surface, before it joined a vertical bundle of copper wires. This scheme utilized the fact that the thermal conductivity of constantan is about one-seventeenth that of copper. In another (sketch c), copper and constantan wires both ran laterally before joining at each thermocouple. This scheme was used where gradients were steepest. Clusters of thermocouples (sketch d),



each thermocouple with leads independent for a length of several feet, were used in the study of small scale temperature field details, where gradients were steep in unusual directions, or where much flexibility was required. Most of the sets used where gradients were relatively steep, as in the snow-cover and in the lower layers of the air, had thermocouples spaced two inches apart. In the air sets with thermocouples spaced six inches, one foot, and ten feet apart were used also. Sets with spacings of 1 cm. and 5 mm. and arranged as shown in sketch c were used at or near the snow surface. The sets were usually used vertically, but some were occasionally used at an angle to achieve a different vertical spacing of thermocouples. Most of the sets were maintained in semi-permanent installations.

Because of the lead resistance limitation, and the fact that the recording potentiometer could be used only in a heated space of roughly constant temperature (such as that of the laboratory) it was necessary to use other instruments to obtain measurements at the more distant field stations. The best portable instrument available was a Leeds and Northrup type 8662 portable potentiometer. It was used equilibrated to the cold, but with batteries kept warm within the observer's clothing. Though accurate it was bulky, heavy, and slow-reading, hence difficult to use over long periods of time or on long trips afoot. It could be connected to any thermocouple or thermocouple set, including those normally connected to the Brown record, by means of standardized switches and plugs.

Another good portable instrument consisted of a thermistor at the tip of a slender rod probe, which was marked off in inches, and a specially devised bridge circuit utilizing a microammeter. This was used equilibrated to the cold, battery kept warm, with frequent calibration adjustments, as a direct-reading instrument. It was sturdy, small, light, and rapid-reading, but was somewhat hard to read with the desired precision. The most useful thermistors used were Western Electric thermistors type 14B.

Standard and arctic alcohol minimum thermometers were used extensively. These instruments provided only a few values each day, at each reading the temperature when read and the lowest temperature since the last reading, but were very useful nevertheless. Though subject to a variety of errors, usually not serious in this research, most were notably reliable and reasonably accurate. These instruments were tested for a period of days or even weeks at the test station. There faulty samples were discarded, matched pairs were selected, and all were roughly calibrated. Then they were placed semipermanently at the field stations. About 25 were used.

Standard mercury maximum thermometers were also used in numbers. These instruments also provided only a few values each day, at each reading the temperature when read and the highest temperature since the last reading, but these data often represented important, even critical, bits of information. They were useless at temperatures below -38°F, and since they were subject to large radiation errors, they were easily damaged, and many were hard to set, they were of limited usefulness. About 20 were used.

Several varieties of "six's" type maximum-minimum thermometers were used. The best were Taylor type 5449 special mercury alloy low range (-60°F) instruments. They provided few, but often important, data and were of limited accuracy, but were very reliable and convenient to use. Another type of maximum-minimum thermometer, the Taylor bimetal type 5321, performed similarly but was more bulky and at times less accurate.

Several types of thermographs were tried. None were very satisfactory, and some were totally useless. The most useful type was the Bacharach "Tempscribe" (two models: using charts S-444 and S-261). This type was small, rugged, usually reliable, and fairly accurate, but did not work at temperatures below -30°F. All the available thermographs failed at low temperatures (as below -30 to -40°F). Because of time limitations it was not possible to procure more suitable types or to develop more effective "winterization" procedures. This type of instrument has great potential value as a field instrument for the determination of temperature structure by means of families of time series.

A number of other types of thermometers were used including a terrestrial radiation alcohol minimum thermometer, a black-bulb radiation mercury thermometer, soil alcohol minimum thermometers, low range thermometers, precision calibration thermometers, laboratory and field alcohol and mercury types, and others.

Wind. Air-mass wind conditions were measured continuously by standard anemometers at the Ladd and other weather stations. These data were most useful during windy periods, and in windy regions. At such times, and places, the wind conditions at anemometer height differed little from those of all but the lowest microclimatic zones. During periods of low wind speeds the anemometer data often represented only local wind conditions in a layer of air at a level above that of the standard shelter, conditions quite different from those of the lower microclimatic zones. Even then, however, the data provided information on atmospheric unrest and stability. Low wind speeds (as from 1 to 10 miles per hour) in the microclimatic zones were measured by small vaned anemometers, and a Bacharach "Florite" air velocity meter. Air motion and drift during "calm" periods were observed and measured by means of suspended materials, such as smoke, condensed water vapor, ice-crystal and ice fog particles, and light chemical bubbles.

Sky. Standard data on clouds (type; distribution: altitude, amount, position; direction of motion; and development) and on fog (type, density (visibility), position, motion, and development) were obtained at least every hour at the weather stations, and were very useful. Supplementary observations were made in the field by the author when necessary and possible. Such observations provided essential information on the nature of, and changes in, current weather states and on radiation conditions. Since the radiometers available for the study of radiation conditions and effective surface temperatures (particularly of the sky) were inadequate, and all failed before any useful quantitative data could be obtained, it was necessary to rely upon less direct sources for information on these very important matters. The most useful such sources were temperature field details and observations on the state of the sky.

Snow. Observations on snowfall (duration, rates, amount) and snow depth were made routinely and frequently at the weather stations. Supplementary observations on snowfall and more complete observations on snow-cover conditions were made at the field stations. Depth and depth changes were measured by means of a) slender wooden stakes, boldly marked off in inches, semipermanently placed, and in some cases read from a distance with binoculars, b) slender rods marked off in inches, fractions of an inch, centimeters, and millimeters, and c) thermocouple sets with fixed spacings. Snow density was determined by obtaining a known volume of snow (usually 223.3 cc) from a particular place and level in the snow-cover by means of a special corer and weighing it in the field (as snow) or in the laboratory (as water). For reference in a comparative study of the changing structure of the snow-cover a few polyvinyl-formal plastic replicas were made.

Information on other matters of lesser or less direct importance, including humidity, pressure and pressure change, precipitation, air-mass development and movement, stability, radiation, and others was gained from standard weather stations using standard procedures or from data and observations taken in the field.

Stations and Network

The field stations were of several types and served several purposes. Some were instrumented and used for quantitative observations, while others, equally important, were primarily for qualitative observations. Some were used to determine small scale details of local temperature fields, while others were used to pinpoint major features of the greater, large scale, field of which the local fields were merely minor components. Most were selected because of the animals living or active in the included habitats, but some represented zones where animal activity was rare or absent. The most important stations served all these functions. They included the following:

Test Station. Located just west of the laboratory this consisted of a standard weather shelter with maximum, minimum, calibration, and other thermometers, and thermocouples, and of a tree upon which were exposed a variety of thermometric instruments. Most of the instruments used in this research were tested at this station. The Ladd standard station was about 4000 feet south and a little east of this station and on a slightly higher area of valley lowland.

BL Station. Also west of the laboratory, at and near the eastern edge of a poplar grove, and some ten feet east of the test station was this important microclimatic station. At it were a) a thermocouple set with 2" spacings used in the snow and lower air (temporary), b) a set with 1 foot spacings used in the lower air (temporary), c) a set with spacings of ten feet for the first 60 feet used in the air, d) free thermocouples used in the air, in the snow, in the soil, and at the interfaces between air and snow and between snow and soil, e) the two radiation thermometers, f) a thermograph (temporary), and g) snow stakes and other equipment. The test station instruments also provided data for this station.

Tree Station. Also in the laboratory area, some 80 feet south of the BL station, was another quite different station. It was based upon a chickadee roost in a double natural cavity some 20 feet up in a poplar tree. A cluster of ten thermocouples was used here. Some of the thermocouples were placed in the cavities, others were outside on the south (sunlit) and north (shaded) sides of the bole. Other, less important, stations were also in the laboratory area.

SD Station. In the small depression were a) two thermocouple sets with 2" spacings used in the snow, one extending into the lower air layers, b) a set with spacings of one foot for ten feet used in the air, c) a set with spacings of 1 cm. for about 1 dm., d) free thermocouples used at the soil surface, at the upper snow surface, in the ice-bath, and in the air, e) one or more each of minimum and maximum thermometers and at times a maximum-minimum thermometer, f) a thermograph (temporary), and g) snow stakes and other equipment. During the first winter period the large depression nearby was equipped with a thermocouple set with 2" spacings used in the snow and lower air layers, and maximum and minimum thermometers.

Bar Station. Several instrumented stations were located in the Bar Area: a) one on the south side utilizing minimum thermometers, and at times a maximum thermometer, b) a similar one on the shaded north side, and c) one including a thermograph and minimum thermometers on the north side in the wide grassy area. Snow stakes were located at these and other places in the Bar Area. Non-routine quantitative measurements were also made in this area by means of thermocouples, thermistors, and wind instruments.

West Bank Station. This simple station was located on the bank top directly west of the laboratory. At it were minimum thermometers, and at times a maximum thermometer. Occasional measurements were also made here by means of thermocouples, thermistors, and wind instruments. Similar stations, the East Bank and River Stations, were located on the east bank (top, side, and base) and river surface directly west of the laboratory. Snow stakes were used at all these stations.

Birch Hill Station. At this station in the spruce woods of the Birch Hill Squirrel Area were a) a maximum-minimum thermometer at a height of four feet, b) minimum thermometers, c) a thermograph (temporary), and d) snow stakes and occasionally other equipment. Occasional measurements were also made by means of thermocouples, thermistors, and wind instruments.

Measurements made with these, and other, instruments were also made repeatedly but not routinely at a number of other less important stations.

In the determination of details of local temperature fields the most useful stations were those reached by the recording potentiometer system. The most important of these were the BL and SD stations. Using portable equipment some determinations of this type were also made at the other stations and at other selected habitats. The stations listed, taken as a group, and including the Ladd station, formed a network with which it was possible to determine major features of the greater or large scale temperature, wind, and other fields. Valley lowland data were provided by the Ladd Test, BL, Tree, West Bank, and East Bank stations. Data on the colder conditions of the lower and lowest areas were provided by the SD, Bar, River, East Bank, and large depression stations. Data on the warmer conditions higher in the atmosphere (which were usually present during midwinter) were provided by radiosonde ascents at the Ladd and Fairbanks stations, by the higher thermocouples of the BL station, and by the Birch Hill station.

Non-instrumented stations used for routine qualitative observation of environmental conditions and animal activity were too numerous to list separately here.

Observation Circuits

To economize the limited time and energy available for this research routine observations were made along prepared fixed routes each forming a circuit linking a variety of instrumented and non-instrumented stations and passing through a variety of microclimatic zones and habitats. Numerous occasional special observations and special studies were also made on these relatively well studied circuits. The circuits were run as often as possible, but somewhat less often than was desired. The most important circuits were four in number:

1) The West Area Circuit ran from the BL station westward to the East Bank station, down to the River station, up to the West Bank station, northward along the top of the bank through the West Bank Area, then on the bank along the river northeastward to the north-south road, southward along the

road and back across the river to the tongue of lowland, and back to the BL station. It usually took about one-half to one hour to run.

2) The Bar Area Circuit ran from the north-south road at the north bank, eastward to the western flat of the bar, eastward along the south and river side of the bar to the east end, then northward across the bar and westward along the north side through the wide grassy flat, by the narrow channel, and along the north bank, then southward through dense willows and back to the western flat. It usually took about one-half to one hour to run, and was at times run in the reverse order. It was often run as an interruption of the West Area Circuit.

3) The Small Depression Circuit, the shortest, ran from the BL station westward along a road then southward along another road to the SD station, and from there back by the same route, or back by roads going eastward, northward, and westward back to the BL station. It usually took about 30 minutes to run.

4) The Birch Hill Circuit ran from the BL station to the north-south road and along it to the base of Birch Hill, then upward and eastward along the diagonal road, past several snow stake and non-instrumented stations, to the Birch Hill Squirrel Area, and from there back by the same route, or on eastward down Birch Hill, then westward along the base of Birch Hill to the north-south road, and southward to the BL station. It usually took from one-half to two hours to run (using a motor vehicle except at the Birch Hill Squirrel Area).

An attempt was made to run the circuits during all types of weather conditions, and at all times of day. The first two were usually run once, during early or mid-morning, or twice, in the morning and in the late afternoon, but frequently were run at other times, and sometimes were run more often, occasionally every two hours. The third was usually run several to many times each day. The fourth was usually run once each day, often in the late afternoon, but was occasionally run several times in one day. Each circuit, where not a road, had a narrow well-packed path in the snow which usually could be walked without snowshoes. Snowshoes, however, were sometimes essential, and were usually used on the Bar Area Circuit. As these circuits were run the observations, quantitative and qualitative and on environment and animal activity, were recorded in a series of field notebooks, and the instruments were maintained and reset.

A few other circuits were run occasionally but repeatedly. The most important of these were the valley lowland loops which were run in several ways but included the road eastward along the river, the road along the base of Birch Hill, and the Chena Trail. Another on this lowland area ran westward to a garbage dump and back by several routes. Another ran about the tongue of lowland south of the river. The exploratory circuits, run only once, were also informative, and were usually not repeated only because of time limitations. As most of them required trail breaking they were time consuming, exhausting, and hard to justify except as special studies.

Special Studies

Under this heading are included those studies which were neither routine nor often repeated, but which provided important information nevertheless. They were carried out infrequently primarily because of time limitations and their secondary importance, but also in some cases because of their essential difficulty, or because of inadequate equipment. Such studies were both local and regional, and geophysical and biological.

In the local area, and to a considerably lesser extent elsewhere, geophysical studies were made of: a) snow conditions - depth, variation in depth, density, settling, metamorphosis, gross structure and crystalline structure, frosting, evaporation; disturbance due to winds, falling materials, animal and human activity (especially packing); other effects of winds, surface temperatures, sunlight, shade, slope, exposure, vegetation; migration, duration, seasonal variability, and others; b) soil temperatures and soil surface temperatures - spatial variation, temporal variations; the effects of weather state, exposure, snow-cover and other insulation, altitude, disturbance, and other factors; c) temperature microstructure about twigs, trees, other vegetation, other objects, exposed soil, and in other situations; d) conditions in tunnels and dens; e) conditions over ice, under ice, in oven-like "sun pockets", and in other special situations; f) radiation conditions; g) wind and drainage conditions - structure of the motion, rates, directions, stratification, waves, channeling, accumulation, and other phenomena; h) the effects of winds on other environmental factors - on temperature fields, snow-cover; blowing snow, dropping snow, moving vegetation; evaporation; turbulence; and other matters; and i) the effects of other factors such as ice fog and depth-hoar.

Occasional repeated or exploratory biological studies or observations involved: a) animal activity - place, time, type, extent; response indicated; food selection, food abundance, seasonal and other changes in the food supply; tunnel systems, dens, nests; ecological relationships such as predation, competition, cooperation; and other manifestations of activity; including b) animal distribution and abundance; and c) the state of animals, involving pelage, leanness, breeding, and other matters; and d) botanical matters such as vegetational type, distribution, abundance, association; vegetational condition as during a cold-snap, in subnivean zones; and others.

Such studies include those made on circuits run only once, such as a fairly long one run on skis near College, Alaska; and other studies, such as one of a cold-snap break-up made on a side and summit of Birch Hill one afternoon. Because of the prevailing scarcity of sound relevant information such studies were often important, and at times were the only sources of needed evidence and information. Of course the evidence they provide must be interpreted very cautiously. Needless to say on these matters much research remains to be done. The special geophysical and biological studies made at other places in the continental interior and in other regions of Alaska, as on the coast westward, and on the Arctic Slope, were made to obtain information on the generality of the Fairbanks results, and to provide information on contrasting conditions elsewhere, but they also permit a more full interpretation of the Fairbanks results.

III. RESULTS

Scope. The results presented here are details for only a few selected periods and places. These represent typical and important aspects of the winter conditions of the continental interior, near Fairbanks, and a few important aspects of the winter conditions on the Arctic Slope. Here no attempt is made to achieve any high degree of completeness in the space-time descriptions of the environmental conditions. A more complete description, while desirable and possible, was impracticable. The results presented were selected primarily because of the importance to the animals of the conditions represented, but also because of the fundamental importance of the phenomena and principles illustrated. In most cases they were representative of the better data. The details not presented were omitted primarily because of time limitations.

Environmental Conditions in the Alaskan Interior

Macroclimates

Ordinarily macroclimatic data are obtained at standard weather stations employing standard instruments, standard procedures, and standard weather shelters. The standardization is necessary to maximize the comparability of the data obtained. As stated previously these data are supposed to represent air-mass conditions or conditions little affected by local surface influences. It is data of this type which are averaged and tabulated or plotted in texts and references on climatology. Yet not only do these averages not represent the events to which the animals respond, but also they do not always represent air-mass conditions. For example, most of the time in midwinter in the continental interior of Alaska, as near Fairbanks, they represent microclimatic conditions, conditions strongly affected by local surface and other influences. Thus at times the standard stations may be useful additions to a network of microclimatic stations, but may reveal little concerning the macroclimatic conditions. Actually it is not easy to say what the true air-mass conditions are, nor where true macroclimatic stations should be placed, when such subarctic continental winter conditions prevail. In this research the "macroclimatic" data of the standard stations were considered to be microclimatic, in conformance with reality. However, in conformance with convention they will be termed macroclimatic data. Such data do represent, in a crude way, the "climate" at Fairbanks, for example. They are truly macroclimatic in summer, when thermal convection prevails, and in winter when mixing due to winds is pronounced (or occasionally when thermal convection prevails).

Typical winter conditions at Fairbanks

These conditions are a sequence of events, a sequence of states (weather states and other environmental states) and of more complex events (such as cold-snaps and storms) composed of several to many states. Figure 3, a compact but crude conventional representation, represents the sequences of temperature conditions at Fairbanks for three midwinter periods. These data

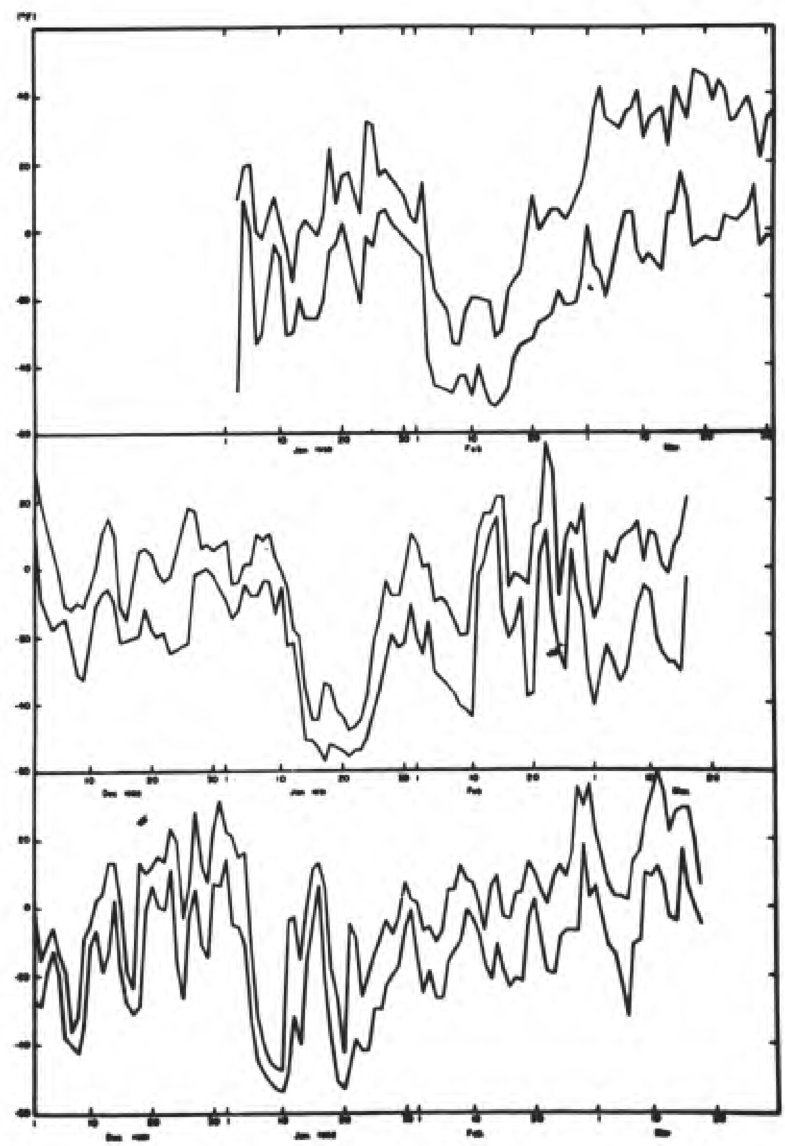


FIGURE 3

are standard station maximum (upper curve) and minimum (lower curve) temperatures, respectively the highest and lowest temperatures measured by standard maximum and minimum thermometers in the 24 hour period from 0000 to 2400 each day. (Note that two successive minima may refer to the same night, and that the maximum (or minimum) of one day, at 2400, may be the minimum (or maximum) of the following day, at 0000, during a period of continuous rise (or fall)). These curves emphasize the variability of the winter conditions: a) a variability from year to year in order, intensity, duration, and frequency of occurrence of the major events which is of high degree and characteristic of the region; b) a variability within months, weeks, periods of several days, or periods of other lengths; and c) a daily variability, indicated by the spread between curves. Each of these winters had at least one severe cold-snap, and had a number of lesser cold periods. Each had midwinter warm periods. Each had prolonged periods of temperature rise and of temperature fall. An alternation, of widely varying regularity, of warm and cold events is also apparent. These sequences may be thought of as consisting of cooling periods interrupted by various kinds of warming events, since the entire midwinter period is essentially a cooling period or potential cooling period. They reflect the passage over or near the region of a succession of "highs" (high pressure centers, which tend to be self-perpetuating in this region at this season) and "lows" (low pressure centers, which tend not to be well developed over the continental interior in midwinter), and represent periods of air-mass development, conflict and movement. Fairbanks lies in a marginal zone of conflict and change between a more southern zone where the cooling influences rarely dominate for long (largely because of the proximity of the Pacific Ocean) and the more northern continental zone where the cooling influences may dominate considerably more. The continental interior is a source region for cold air-masses in winter thus these tend to develop or intensify there during the periods of cooling, only to move away in response to the movement and development or other pressure systems, or to be broken up and dissipated by storms. The interrupting storms are chiefly 1) snowstorms, or cyclonic or frontal storms, which are usually poorly developed over the interior in winter, although apt to be vigorous along the coast a short distance to the south (from where they rather frequently send clouds over or extend over the interior); and 2) windstorms, which result from strong pressure gradients of several kinds (including local and air-mass cyclonic, anticyclonic, and frontal system gradients).

These events and their structure, changes, and interactions are better visualized when studied in more detail. A few selected examples will suffice to show the main features of typical weather states and other weather events as revealed by macroclimatic temperature data.

Weather States and Weather Events

The main details of these events are effectively revealed by time-series giving temperatures every hour (in the following plots approximately on the half hour). Only a few important characteristics, properties, and associated conditions can be described here.

Cold periods. The weather event of greatest interest in this research was the severe midwinter cold-snap (see fig. 4). This figure shows the Ladd data for the most intense cold-snap of the second winter period of research (see also fig. 3). This event, typical of such events, had four main stages: 1) the initial period of rapid cooling (during the early hours of Jan. 5), 2) the phase of unsteady cooling, cooling proceeding at a decreasing rate (up to Jan. 9), 3) a phase of relatively steady conditions

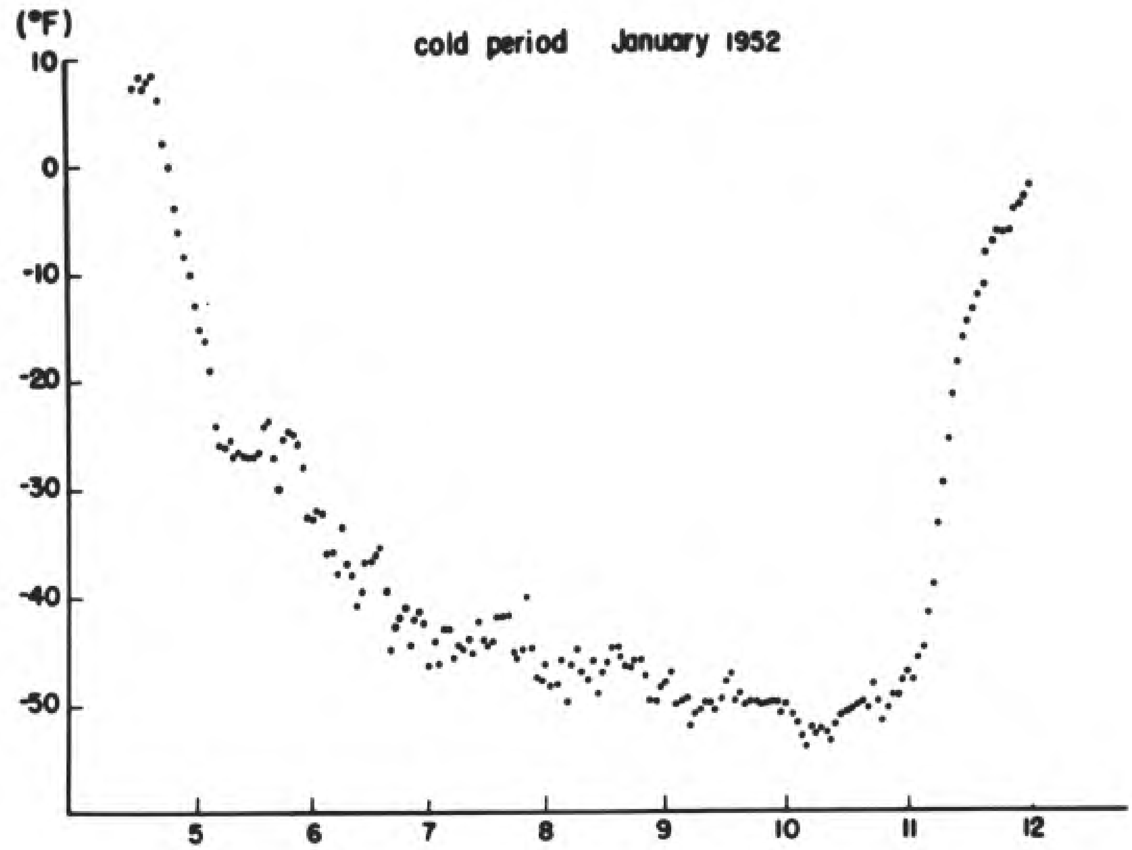


FIGURE 4

(roughly from midday Jan. 9 to midday Jan. 10), and 4) the final break-up period of rapid warming (from midday Jan. 10 to Jan. 12). The relatively steady, uniform conditions of the evening of January 9 typify a cold weather state. Speaking less precisely the cold period from January 8 to January 11 represents a single very cold state. The conditions during this very cold period were typical of those of intense cold-snaps. They included: a) a long dark night, b) a short period of daylight (about 4 hours in early January becoming 8 hours by mid-February) with low sun and relatively long periods of bright twilight, c) little diurnal temperature variation, d) very little air motion (winds reported calm), e) clear skies, f) very stably stratified air with a steep temperature inversion in the lower layers, g) subsiding air and a surface high pressure system over the region (both to

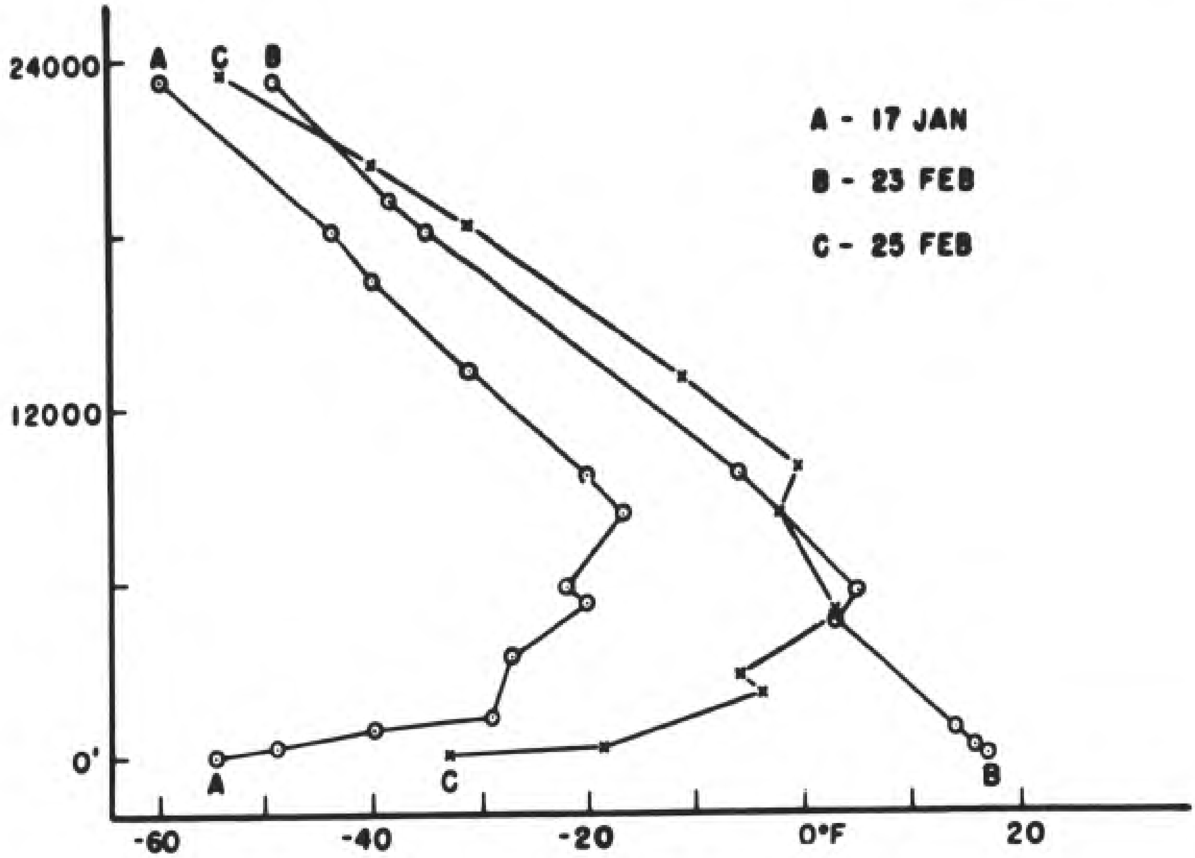


FIGURE 5

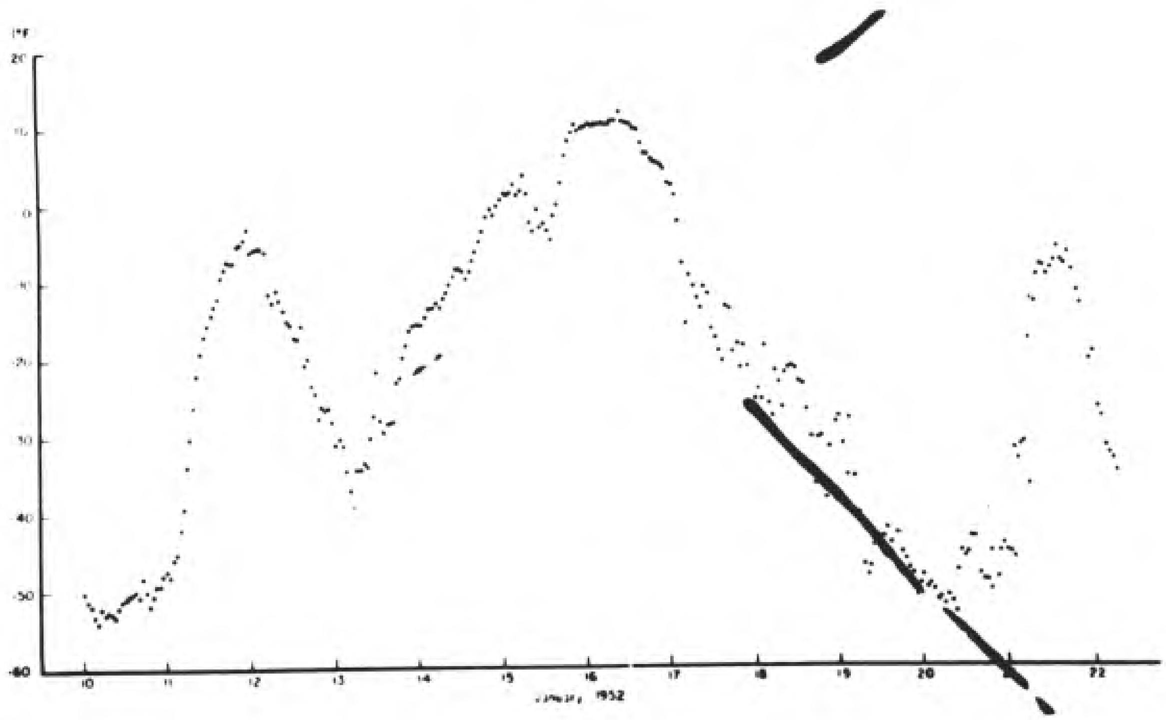


FIGURE 6

a large extent a cause and a consequence of the cold-snap conditions), h) considerable frost deposition, and i) formation of ice-fogs (which may become exceedingly dense in the vicinity of settlements). Typical temperature conditions at the standard station and above during a cold-snap are shown in figure 5, for Ladd, about 0500 AST, 1951. The cold-snap curve, curve A, shows: a) the sharp temperature inversion (increase of temperature with height, a reversal of the usual temperature decrease with increase in height) here sharp below about 6000 feet, and sharpest in the lowest 2000 feet of air, b) the overlying zone of maximum temperatures, here at about 8000 feet, and c) the more usual atmospheric gradient above 8000 feet; (see also fig. 3). Similar conditions, differing mainly only in degree, occur during the less extreme cold periods. During these the temperatures usually do not fall so low, and when they do, do not remain low so long. Such lesser cold periods are, of course, more frequent (see fig. 3), and may have well developed inversions (see curve C, fig. 5). Two other cold periods, the second a true cold-snap, are shown in figure 6. The cold-snap, the second of the winter, has the same four stages seen in the first: 1) a period of rapid fall (during Jan. 17), 2) a period of unsteady fall, followed by 3) a relatively steady period (during the early hours of January 20, later obscured by diurnal heating), and 4) a period of rapid rise (on Jan. 21). The effects of diurnal heating are more apparent during this later cold-snap. More details on these and other cold periods are presented later in the section on microclimates.

Warm Periods. The sequence depicted in figure 6 also shows several types of warm periods, (see also fig. 3). The first (from the morning of Jan. 11 to the afternoon of Jan. 12) was a passing snowstorm, which broke up (or interrupted) the preceding cold-snap. A short windy period with windspeeds of 10 to 15 miles per hour occurred in the late morning of January 12, a common occurrence following the peak of such storms. In this case the effects of the winds are scarcely apparent. The second warm period event (from the night of Jan. 13 to the early morning of Jan. 17) was a multiple snowstorm (a storm with three periods of snowfall separated by periods with lifting clouds and some clearing). Clouds and some snowfall occurred on January 14 and January 15. Clearing and cooling, represented by a dip, occurred about midday on January 15. Following this the major storm, with relatively heavy snowfall (about 9 inches), occurred starting near midnight on January 15, developing winds about noon on January 16 (these strengthening to 10 to 20 m.p.h. in the evening), and ending about midnight on January 16. The relatively steady, uniform conditions at the peak of the storm represent one weather state, a state with high temperatures, a low overcast, no wind, and relatively heavy falling snow. Another state existed during the windy period, a state with high but slowly falling temperatures, a low but more ragged overcast, moderate winds, and moderate snowfall. A period of rapid temperature fall followed the sudden clearing on the morning of January 17. The last warm period event of this sequence was of quite a different sort. It represents a windstorm without clouds or precipitation. It started about 0400, January 21, developed winds of speeds of about 10 to 20 m.p.h. which persisted until about 2200, and then ended as the winds weakened and the temperatures fell again. This type of warm period was not common. Later in the season a third type, that of warm periods due to diurnal heating, became more apparent and more important (see below).

The temperature conditions at and above the standard station during a warm period (a windy snowstorm) are typified by curve B, figure 5. In this figure changes occurring following the passage of a storm (curve B) are shown (compare curve C). Clearly most of the cooling occurs in the lowest layers of air. Similarly when a cold-snap breaks up most of the warming occurs in the shallow layers of cold air near the surface.

Intermediate and Transitional States. A variety of transitional and intermediate states may be distinguished (see figures). The events of rapid cooling preceding cold periods, and of rapid warming during their break up, and of the analogous periods of the diurnal cycle are of particular importance to animals. Others, for the most part, will not be considered in this paper.

Regular Events. In addition to the regular events of continuous cold (January 10, 1952), continuous warmth (most of January 16), steady fall (night of January 4), and steady rise (most of January 11), there is another important type of regular event, that of periods of (relatively) regular periodic diurnal variation (see fig. 7 and also fig. 3). Figure 7 shows three sequences for such compound events occurring during 1951: 1) one for the January cold-snap showing the low diurnal amplitude, the long cold night period, and the relatively brief period of daylight at that time; 2) one for the main February cold period showing the higher amplitude during this more sunny period, and showing the cold night still appreciably longer than the warmer day (in fig. 3 this increased amplitude is indicated by the increased spread between the curves); and 3) one for March showing a still greater amplitude, and showing the cold nights about equal in length to the warm daylight periods. Such events provide replication, for during such periods the days are closely comparable. Furthermore such periods provide the other four main regular events each repeated once each day.

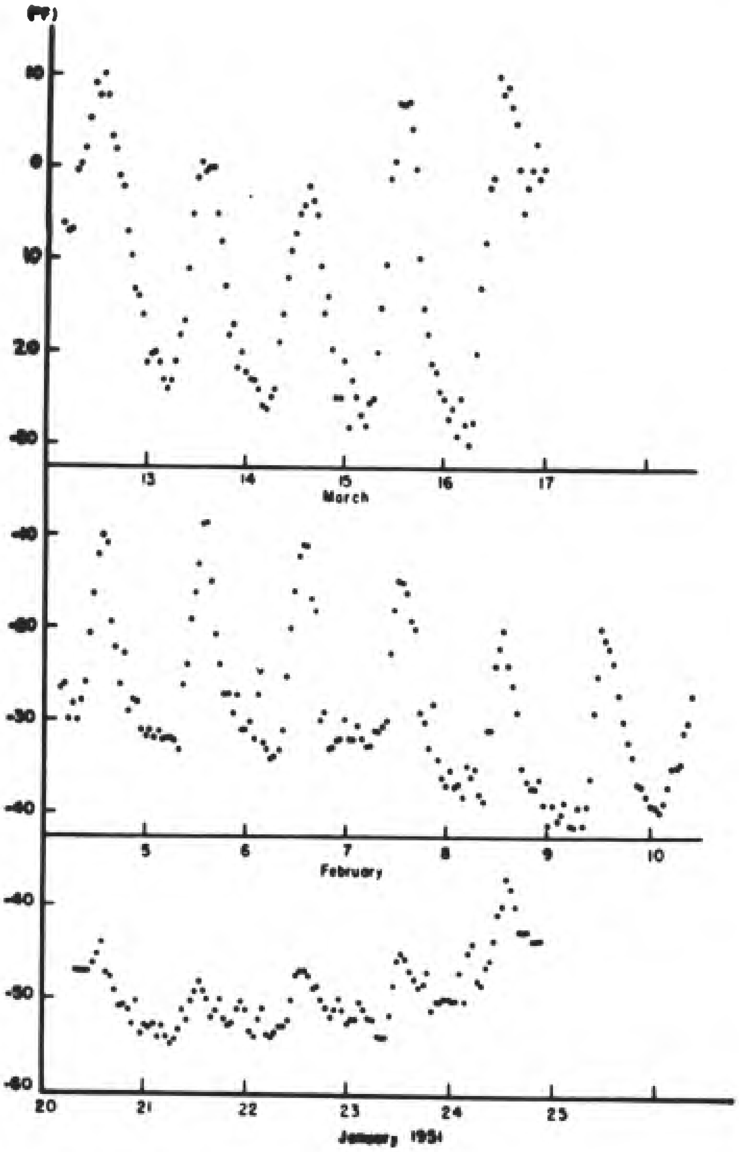


FIGURE 7

Irregular Events. Irregular important compound events and irregular minor events are generally more common than the relatively regular types considered above. They represent an unavoidable complexity. As they may be considered to be made up of many, short-period, simpler, relatively regular, lesser events, they can always be reduced to their lesser components. However, this apparent simplification does not reduce the complexity, but merely redistributes it. All of the long-period compound events, such as the sequences of events of a month or of a winter period (see fig. 3), are conspicuously irregular. Fortunately for this research the winter conditions are far more regular than the conditions occurring during the other seasons. Furthermore, the major events and long-period events were far more regular in the zones of the snow-cover, at the base of the snow-cover, and in the layers of the soil than they were in the zones near the snow surface and in the layers of the lower atmosphere. Events, even long-period events, of the deeper zones of the soil and the ground showed virtually no irregularity. These events were in fact a close approximation to the simplest type of compound event, the event of no change.

Microclimates

For each of the states and events revealed by standard station or "Macroclimatic" temperature time-series there is a corresponding changing temperature structure and set of associated conditions in the zones of the microclimates. The standard station, essentially microclimatic, data form a convenient reference series, compared to which the corresponding changes in the other microclimatic zones may be even more pronounced, considerably less pronounced, or virtually absent. Furthermore, primarily because of heat conduction lag effects, the corresponding changes or events may not occur at the same moment of time in the various microclimatic zones. Not only are the changes represented by the major events greatly diminished in microclimatic zones deep in or under the snow-cover or deep in the soil, but also they may occur considerably later in those zones. In those zones most minor events are reduced essentially to non-existence. While these changes in any of the other microclimatic zones can also be represented by time-series, it is more helpful to return to three-dimensional fields of variables and to use such time-series merely as aids to the visualization and representation of these more fundamental fields.

Leaving microclimates, which occur at a point, to consider microclimatic conditions, which include the conditions at many points, it is thus seen that these too consist of sequences of states (of a more complex type) and of other events (composed of states). Only a few main features of the spatial order (structure) and temporal order (sequences) of these states can be presented here. These represent additional details of conditions of specific states already mentioned, and also a few details of conditions of a few other states and events of, and in zones of, particular importance to the local mammals and birds.

Vertical structure. Because of the high degree of stability and stratification prevailing during most of the winter, horizontal variations in conditions were usually slight over short distances in comparison with vertical variations, which were often extreme. This was particularly the case during radiational cooling periods, hence during cold periods. Because of this high degree of order the winter conditions represent, in the study of environmental conditions in general, an important and instructive simple case. This simple structure is also a winter characteristic of considerable importance to the local animals. Figure 8 shows, semi-diagramatically, typical vertical temperature structure during a cold period. The vertical scale is logarithmic, with the zero reference level ten feet below the ground surface, so chosen to emphasize the details near the upper snow surface. This temperature profile shows: a) typical gradients at the highest levels, b) a temperature maximum at about 4000 feet, c) a typical inversion below the maximum, d) dashed lines in the lowest 100 feet of air to indicate scantiness of data, e) an increasingly sharp inversion as the snow surface is approached, f) a discontinuity at the surface, g) a steep gradient through the snow-cover, h) a warm zone at the

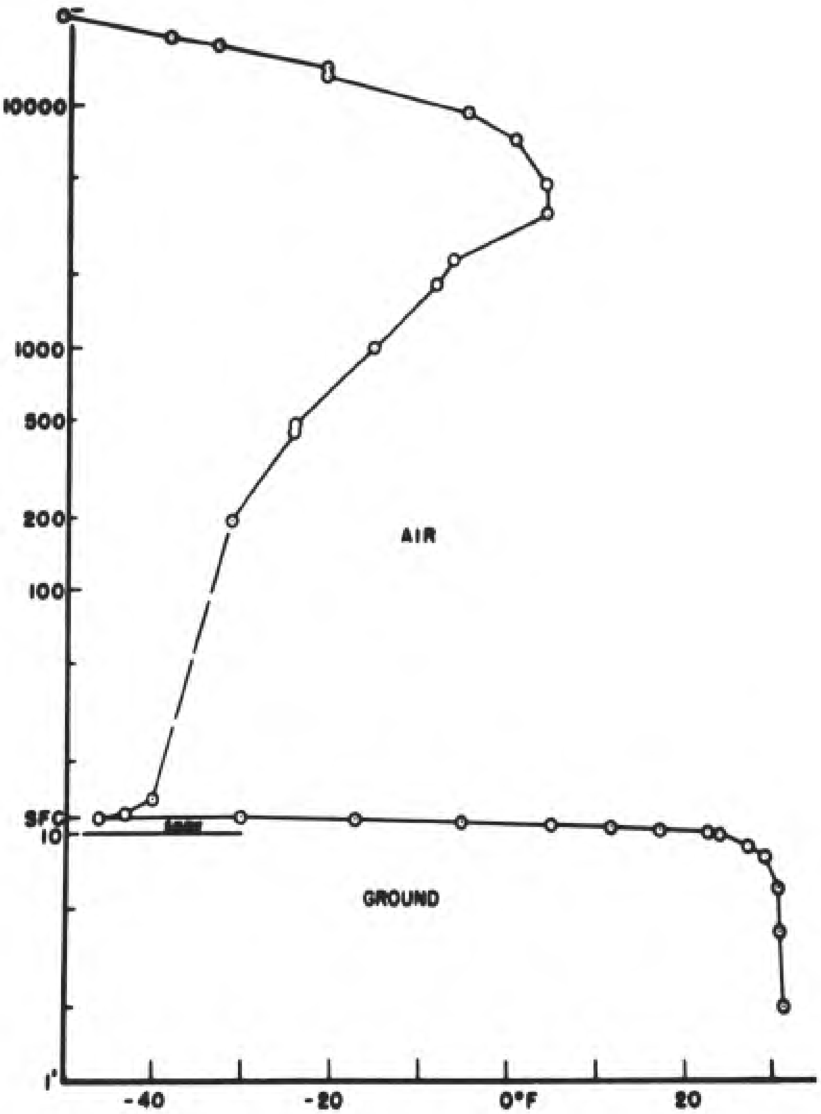


FIGURE 8

soil surface, and i) an approximately isothermal zone with a temperature slightly below freezing at the lower soil levels. Through all of these zones, but particularly in the atmosphere and in the deeper soil layers, the lateral temperature variations were slight. Though informative such representations are very time consuming to construct. More profiles as complete as this one cannot be presented here, but less complete profiles, for the snow-cover and the lower layers of the air, are presented for a variety of environmental states and events in the next section. In the following section a rough picture of the vertical structure, as revealed by temperature data, may be constructed from the temperature time-series curves and the concurrent data of the profiles and associated points.

<u>Cold Periods, Warm Periods, and Other Events</u>. Typical microclimatic conditions, as revealed by temperatures, during a cold-snap are indicated in figure 9. The lower curve gives conditions at the snow surface at the bottom of the small depression at the station SD. The middle curve gives conditions at the snow surface at the station BL. These commonly differed little from those at a height of one or two feet in the small depression. Surface temperatures, being the most informative, being closely and usually simply related to the temperatures of the adjacent zones above and below

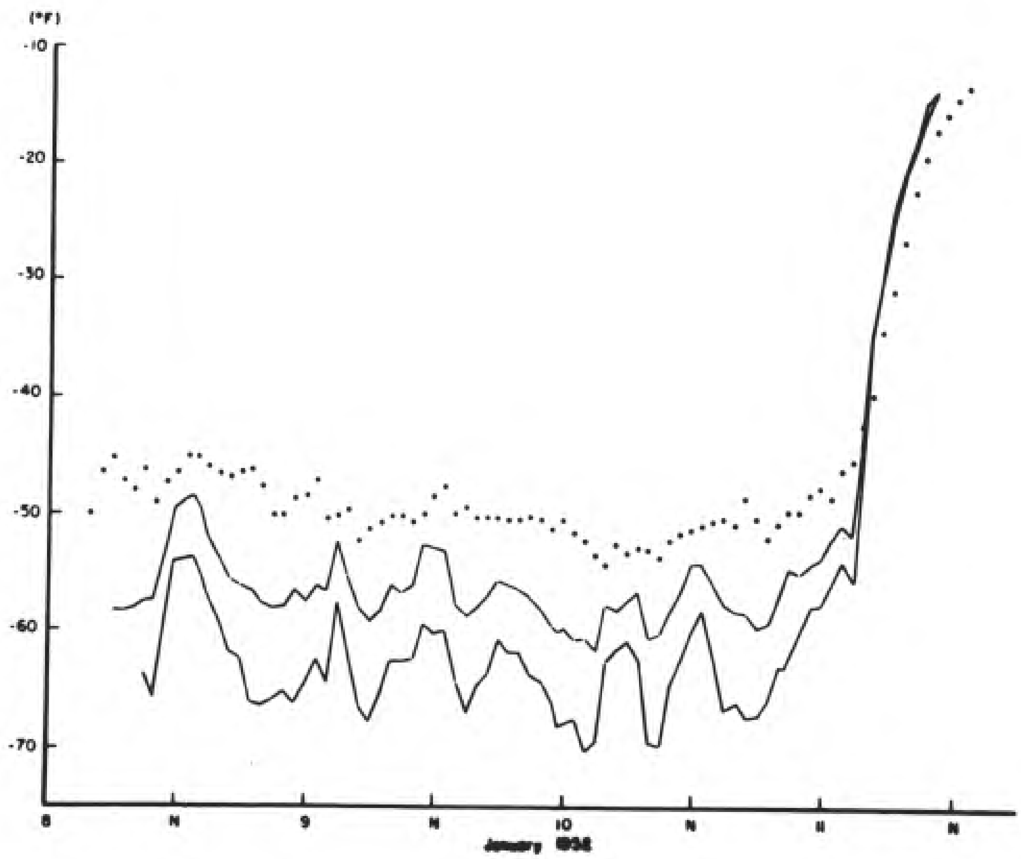


FIGURE 9

and to a large extent controlling those temperatures, and being of considerable importance to animals, were commonly measured and will be presented whenever data for only a few points can be given. The dots give, again, the conditions at the Ladd station. These commonly differed little from those at the 20 to 40 foot levels at the station BL. The values represent hourly data (taken approximately on the half hour) and in some cases half-hourly data. In a few cases data for other times were used as well. The connecting lines are for clarity only, and are not, in general, valid as interpolations. This family of time-series shows two clearly distinct weather events: 1) the stable cold conditions of the winter's most intense cold-snap, and 2) the unstable, convective, warmer conditions of the period of rapid warming which followed the cold-snap (see also fig. 3). During the clear, calm, cold-snap period a number of lesser events are apparent: a) periods of diurnal warming, reaching a peak at about noon each day, most pronounced at the SD surface, least pronounced at the levels at and higher than the Ladd station, and resulting in less steep vertical gradients at midday; b) periods of temperature minima, when sunlight was weak or absent, air motion was least, and possibly also when the ice fog was least dense; and c) periods of nighttime warming due to known variations in air motion (the peaks of the early morning hours of January 9 and of the morning of January 10 are known to be consequences of an increased rate of air movement or drift) and to suspected variations in radiation conditions (the peak of the afternoon of January 9 is clearly of a different sort, and may represent the direct effects of the dense ice fog present, changes in air movement, indirect effects of the ice fog which may include changes in air movement, or other changes affecting radiation conditions - the steadiness of the temperature conditions and the temperature fall in parallel with the decrease in density of the ice fog point to the fog as a major controlling influence). The rise on the evening of January 11 may have been partly due to changes in radiation conditions, for the ice fog was most dense then, but the rates of air movement were also increased. The period of rapid rise was caused by the eastward movement over the area of a sheet of clouds, first a little high cirrus (at about 0400), and then much cirrus, then rapidly lowering to a low overcast. Soon after the clouds arrived the surface temperatures rose above the temperatures of the lower layers of air (because of radiation exchange with the clouds) thus giving rise to unstable convective conditions and rapid warming of the lowest layers of air. Winds were not present during the period shown.

More details of cold-snap conditions are shown in figure 10. In this the curves are: a) lowest for snow surface at station SD, b) middle for

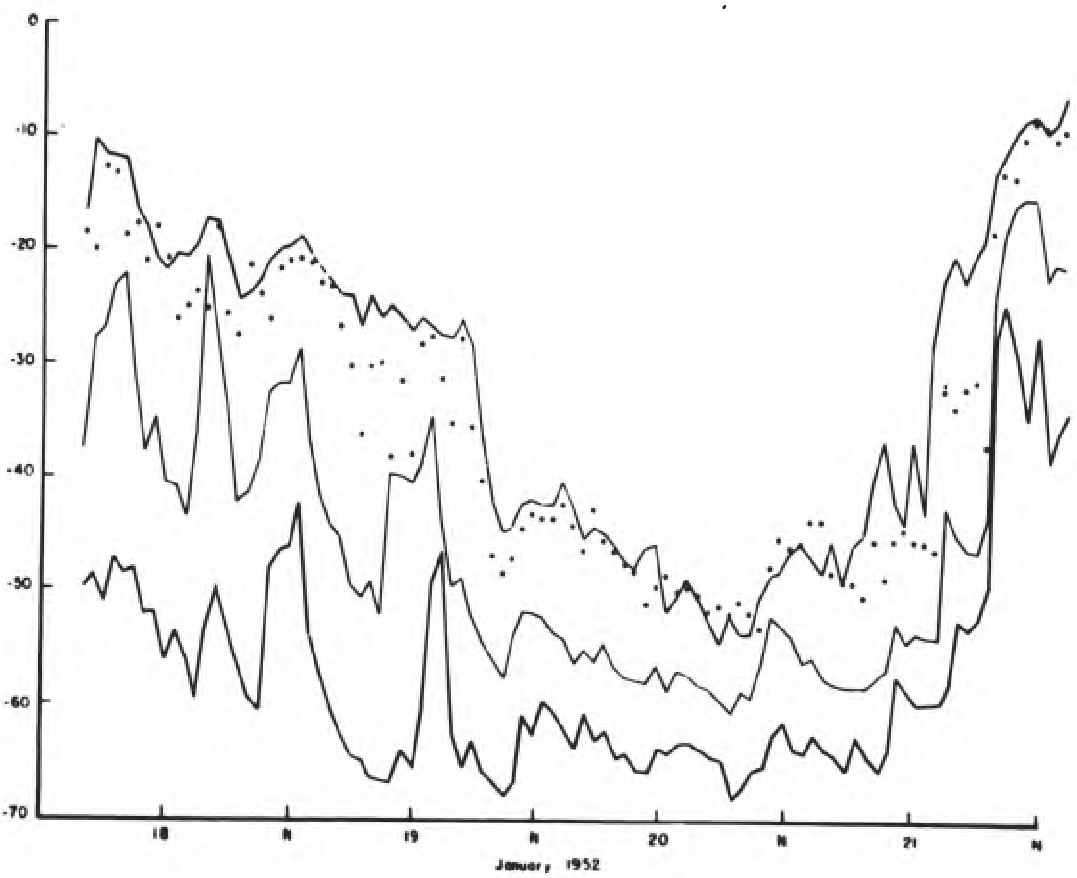


FIGURE 10

snow surface at station BL, c) upper for 40 foot level at station BL (about 50 feet above the surface at station SD), and d) dots for Ladd (see also fig. 5 and fig. 3). The set of time-series curves shows three major events: 1) the stable but unsteady conditions of the early period of cooling, 2) the stable relatively steady conditions of the coldest period, and 3) the period of warming following the cold-snap.

The conditions during the early period of cooling included: a) clear skies, b) no ice fog, c) light winds of variable direction and speed (2 to 10 m.p.h. at Ladd), d) periods of diurnal heating (one obscured by a windy period with winds up to 10 m.p.h., about noon Jan. 18), e) minor events of windy periods (afternoon of Jan. 17, winds to 14 m.p.h., morning of Jan. 18, winds to 9 m.p.h., about noon Jan. 18, early morning Jan. 19, winds to 6 m.p.h.), not closely coincident near the laboratory and at Ladd, f) relatively calm periods with pronounced cooling, and g) steep vertical temperature gradients, least steep during the windy events, most steep during the more calm events (with a difference over the 50 feet above the surface at station SD of over 40°F, as during the evening of Jan. 18). During this period the cooling proceeded faster and farther in the protected depression at station SD, but even there winds were an important disturbing influence.

When the winds died down in the morning of January 19 the coldest period began. The conditions during this event included: a) clear skies, b) moderate to dense ice fog, c) no winds (calm), d) periods of diurnal heating (about noon Jan. 19, and Jan. 20), e) minor events of warming due to changes in air motion and drift (near midnight Jan. 20) or to changes in radiation conditions (possibly primarily due to ice fog) or to both, f) minor events of calm cold periods (as in the morning of Jan. 20), and g) less steep, but still steep, vertical temperature gradients.

The cold period terminated when moderate winds (from 10 to 15 m.p.h.) began suddenly (in the morning of Jan. 21) signifying the approach of a windstorm, which then affected the conditions for about one day. During this storm event the conditions included: a) clear skies, b) no ice fog, c) winds (reaching a peak about noon and thus obscuring any diurnal heating), d) minor events of warming or cooling as the winds strengthened or weakened, and e) steep vertical temperature gradients when the winds brought warm air to the upper levels but before they had blown away or mixed away the stable, cold lowest layers (morning of Jan. 21), and less steep gradients later when the strongest winds mixed the layers more thoroughly. During this event the lowest layers were affected least and latest, and recovered soonest.

Temperature Profiles through the Snow-cover and the Lower Layers of Air

Details of the conditions in the snow-cover and further details of the conditions in the lower air layers, as revealed by temperature data, for one moment of time, may be effectively represented by means of temperature profiles (see fig. 11). This figure, for the station SD, about 2400 January 9 (see also fig. 9, which, however, giving data on the half hour, does not actually show the minimum at this moment) shows: a) the minimum temperature and discontinuity at the upper snow surface (reflecting a continued high rate of long-wave radiation energy loss at the surface, and signifying continued cooling in the snow-cover and in the lower layers of the air), b) the steep gradient through the snow, representing approximate thermal equilibrium in the snow-cover at this late state of the cold-snap, c) the non-homogeneity of the snow-cover, d) the high temperature at the base of the snow-cover and near the soil surface, e) the very steep inversion in the air close to the snow surface, which becomes increasingly less steep upward (but remains very steep on an atmospheric scale), and which represents a high degree of stability and stratification in the lowest air layers, and f) the remarkable orderliness and steadiness of the very stable lower air layers. The conditions in the snow-cover changed little, in general, over a period of many hours, during this stage of the cold-snap. The changes in the snow-cover, at least in the upper layers and especially in the surface layers, were usually considerably more rapid than they were at this time. Changes in the deeper layers were typically as slow or even slower. The conditions in the snow-cover of nearby areas were similar but differed in detail, the differences depending on many factors. At most areas the surface temperatures were not so low, the soil surface temperatures were not quite so high, and the gradients were not so steep as shown in this extreme example. Thus the conditions at the station SD, in comparison with the conditions of nearby areas,

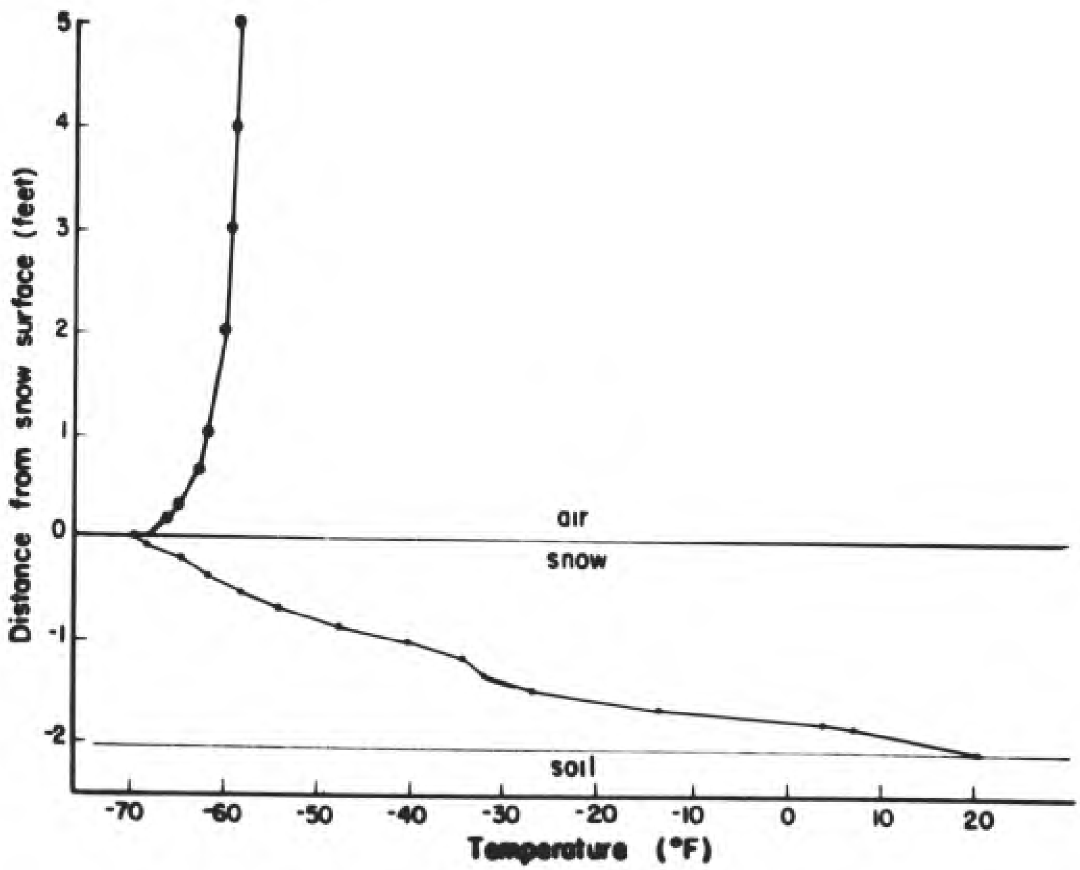


FIGURE 11

are those of a local "cold pocket." The value at the lowest thermocouple is not representative of true soil surface temperatures, being somewhat in error as can be seen from the bend in the curve. Supplementary measurements indicated an error of 6 to 8°F. Because of the roughness of the soil surface, vegetation, the ladder-like shape of the thermocouple set, and the steepness of the gradients, errors at the surface due to faulty thermocouple placement and disturbance were very hard to avoid. The conditions in the lower air layers of other nearby areas were similar but not quite so cold nor so steady.

Turbulence, present in the air during even the calmest natural conditions, occurred to an unusually slight degree in the lower layers of air at the station SD during the very cold period of the night of January 9-10 (see figs. 9 and 11). Because of fluctuations due to turbulence, a constant nuisance and source of error, instantaneous microclimatic temperature profiles in the air tend to be somewhat irregular and to change shape rapidly, sometimes slightly, sometimes considerably. Hence they tend to be uninformative and misleading, though they do indicate the amount of unrest present. Short period averages help to overcome the difficulty. With few exceptions such averages were not obtained or computed in this research, because of instrumentation and time limitations. For these reasons few satisfactory profiles for the air can be presented. Most of the "profiles" shown, presented in connection with temperature profiles in the snow-cover, are only approximately instantaneous, hence show an irregularity of little meaning, except as a measure of atmospheric unrest. Time-series data, with the values taken at arbitrarily fixed times and after relatively long intervals (as here, usually every hour on the half hour), reflect longer period trends and usually do not show the effects of turbulence so clearly, but are affected by them, at times strongly. The single point data presented with the following temperature profiles in the snow-cover to indicate vertical temperature structure, are likewise affected by turbulent fluctuation, and thus apt to be somewhat non-representative. The atmospheric data of figure 9, being exceptionally free of the effects of turbulence and of other changes, form an unusually meaningful approximately instantaneous temperature profile.

Microclimatic Conditions of the Snow-cover and Lower Layers of Air

Further information on the nature of the microclimatic conditions in several zones of importance to animals is provided by the following series of temperature profiles. These profiles and associated point-values indicate the conditions, as revealed by temperatures, in the zones of the snow-cover and lower layers of air at the station SD, and at the surface (upper line) and the 40 foot level (upper dots) at the station BL. These data represent conditions during a variety of weather states and events that occurred during the midwinter and late winter periods of early 1952. Each curve and associated points indicate the conditions at one "moment" or short period of time (of a duration of usually not over 6.5 minutes for all the points, and not over 2 or 3 minutes for all the points in the air). For the curves showing conditions through the layers of the snow-cover and through the lowest layers of air at the station SD, the measurements were made in sequence, usually the lowest first, and the rest following at a steady rate of 4 per minute and giving the values at points spaced 2 inches apart. To this extent the data were approximately instantaneous. Since each curve with associated points presents information representing details additional or supplementary to those already presented in the form of time-series, each should be studied in conjunction with the appropriate time-series. In this way it is possible to amplify the initial crude visualization of the changing three-dimensional fields under consideration. During most of the stable cold weather states, and also during the more homogeneous warm weather states, the 40 foot data are representative of the conditions at the corresponding level for considerable distances horizontally (in general, at least a half mile). The BL surface data are representative of conditions at the upper snow surface of the level, fully exposed (unshaded), nearby areas of the valley lowland. The cooler conditions of valley lowland areas in full shade, in the partial shade of vegetation, and on north-facing slopes, and the warmer conditions of areas on south-facing slopes of the valley lowland represent simple modifications of these conditions. The conditions at the nearby lowest areas varied quite a bit, the differences depending on many factors, but in general were similar to, only more moderate than, those at the SD station. Similarly the conditions in the snow-cover of nearby areas varied quite a bit, depending primarily on snow depth, snow structure, surface temperatures, and topography, but in general were similar to, only less extreme than, those at the SD station. Conditions in the snow-cover in the Bar Area (north side) were approximately the same as those at the SD station, while those at other low areas at or on the river differed chiefly in their somewhat higher surface temperatures (hence less steep equilibrium gradients and correspondingly less cold conditions within the snow-cover). Conditions in the snow-cover at areas on the valley lowland tended to be still less cold near the upper surface, but somewhat colder at the soil surface.

Further details of conditions during the most intense 1952 cold-snap are shown in figure 12 (see also figures 4, 6, and 9). Curve 1, for about 2355 Jan. 7, shows conditions at a time in the stage of unsteady cooling (see fig. 4). Curve 2, for about 1220 Jan. 8, shows conditions at a time near the peak of a period of diurnal heating (see fig. 9). The snow surface has been temporarily warmed, but is still colder than the stable, steady air above. The temperature of the air above is about the same as temperatures at the surface of the nearby valley lowland. Vertical gradients in the air are not very steep, but still represent considerable stability. Curve 3, for about 0140 Jan. 9, shows the effects of a minor event of temporary warming at and above the surface due to an increase in air movement (see fig. 9). Despite the air motion the lower layers of air are still very steady and stable. Curve 4, for about 2400 Jan. 9, shows essentially the same conditions represented in figure 11. The data of the lower air, given in slightly more detail for a slightly different time, reveal the increasingly steep gradients near the surface, and a small amount of unrest in the very stable lowest layers of air. The dashed lines in the snow-cover indicate missing points (missing because of shorts accidently manufactured into the long lead wires). In curve 4 the S-curve in the snow-cover is

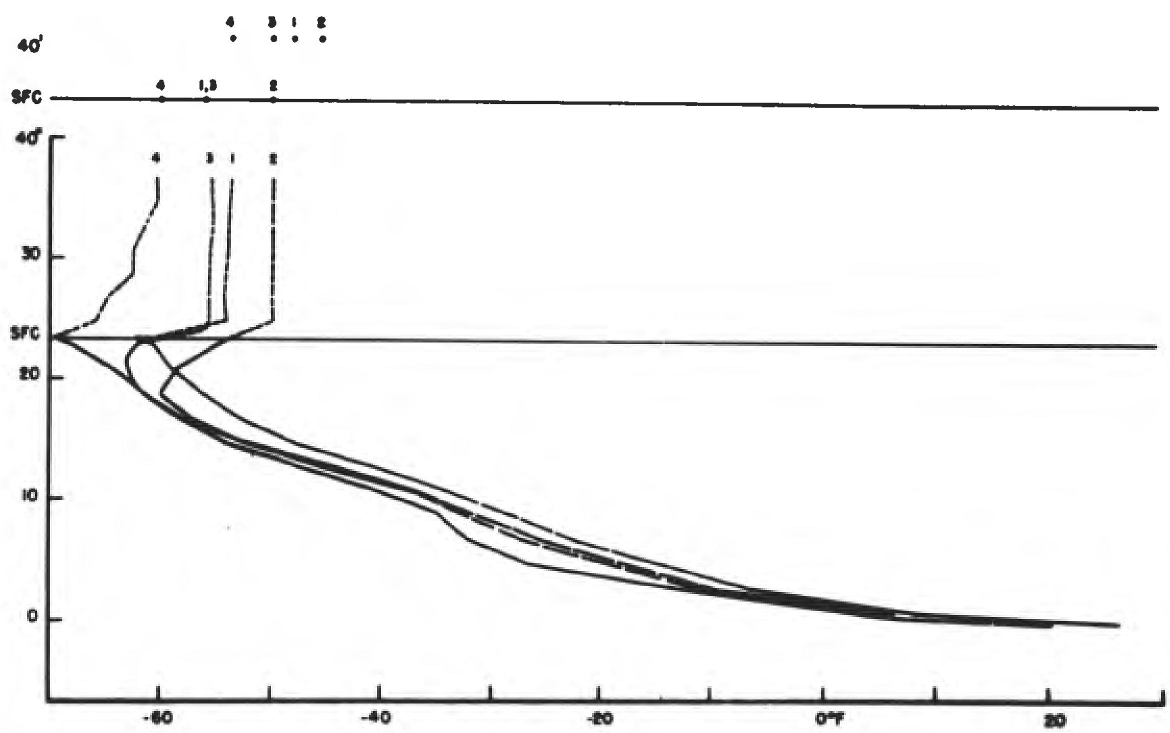


FIGURE 12

partly real (due to variations in snow structure) but also partly an artifact (due to convection within the snow-cover, a process possibly favored by the slight disturbance caused by the thermocouple set). The lowest thermocouple temperatures of these and the following curves are not representative of true soil surface temperatures for the reasons stated above. The slow changes in the snow-cover through this relatively long period of time indicate a close approach to equilibrium conditions.

Figure 13 portrays a variety of situations. Curve 1, for about 1410 Jan. 10, shows conditions after a brief interval of cooling following the period of diurnal heating of the last full day of the cold-snap (see fig. 9). Vertical gradients in the lower air layers are very steep. Curve 2, for about 1900 Jan. 10, shows conditions near the time of minimum temperatures before or just as a period of warming commenced (see fig. 9). An increased unsteadiness in the lowest air is apparent, indicating a general increase in air motion, but the temperatures of these layers still differ

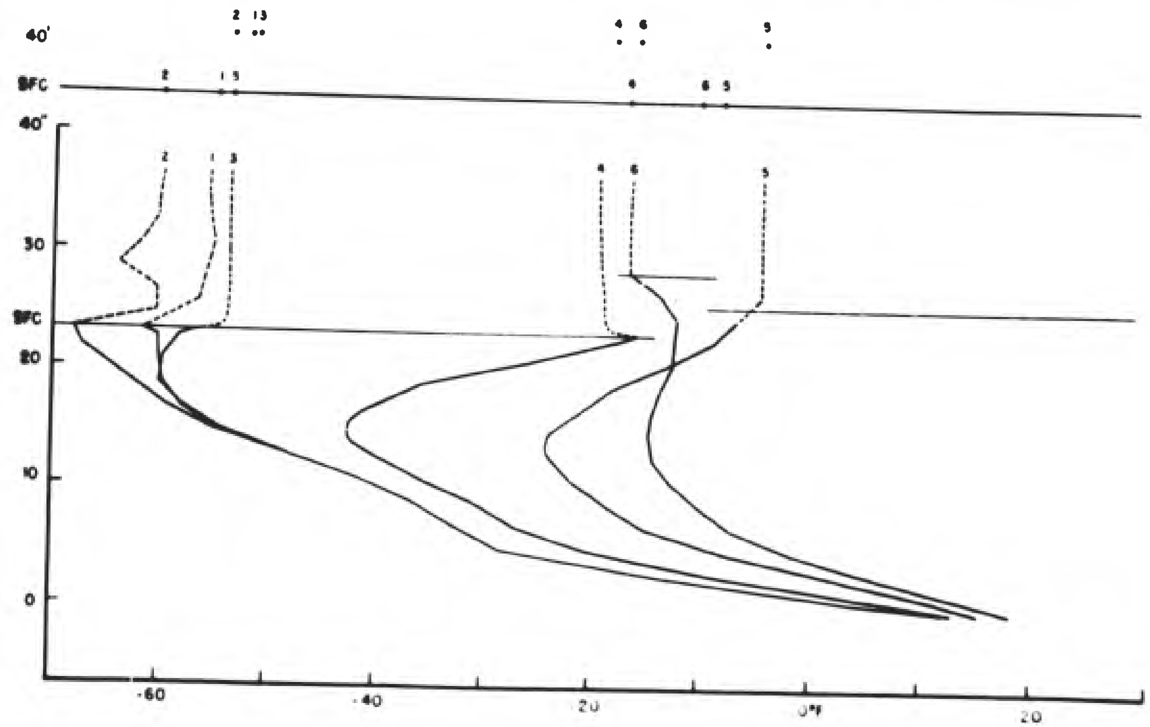


FIGURE 13

little from the surface temperatures of the adjacent areas of valley lowland. Curve 3, for about 2340 Jan. 10, shows further effects of this night event of warming (see also fig. 9). The surface temperatures are significantly increased, the lowest air is momentarily steady, and the vertical gradients in the lower air are so slight that isothermality and non-stability are approched. These curves show that most of the change was confined to zones close to the active snow surface, and that higher in the air and deeper in the snow-cover the changes were slight. Curve 4, for about 1000 Jan. 11, shows the consequences of the movement over the area of lowering solid layers of clouds, during the period of rapid warming at the termination of the cold-snap (see figs. 6 and 9). The snow surface, warmed by radiation exchange with the warmer clouds (in the warmer upper air zones), leads the warming in the snow below and in the air above (see also fig. 9). These effects are apparent at both the BL and the SD stations, and were in fact quite general. The curve represents the extent of warming some 6 hours after the rapid rise began. Some warming during the night had already occurred before the sharp rise began (see fig. 9, and curve 3 of fig. 13). The lowest air layers were non-stable but relatively steady, and had not yet become completely isothermal. Curve 5, for about 2340 Jan. 12, shows some details of conditions near the peak of the snowstorm (see fig. 6). These conditions included: a) snowfall, b) a low overcast, c) no winds, d) relatively high temperatures, e) isothermality in the lower air layers, f) an increase in snow depth, and g) continued warming in the snow-cover, particularly at intermediate depths, but also at the lowest thermocouple. The surface temperatures are missing because the surface thermocouples were buried by the falling snow. The surface temperatures probably differed little from the air temperature. The BL "surface" point gives a value at a depth of several inches, at the surface of the old snow-cover. The dashed line through the SD surface indicates a lack of data and is not a valid interpolation. At this time the coldest microclimatic zone in the area was the zone near mid-depth in the snow-cover. Curve 6, for about 1040 Jan. 12, shows details at a time after the storm (see fig. 6). Conditions then included: a) snowfall, b) an overcast of low but rising and breaking low clouds and of high clouds, c) light to moderate winds (8 to 16 m.p.h. at Ladd) which brought in colder air from other areas (cold air advection) and mixed well the non-stable air, thus d) falling temperatures, and e) approximate isothermality in the lower layers, f) further increase in snow depth, and g) cooling of the surface layers of snow but continued warming at intermediate and lower levels. Surface temperatures are again missing. The BL "surface" point gives a value at a level within the snow-cover (evidently in the zone of maximum temperatures). The SD surface conditions are shown more correctly interpolated, for the surface temperature was known to differ little from the air temperature (tending to be slightly higher). Because of the isothermality the conditions in the lowest layers of air appear steady and unaffected by the turbulence that was certainly present. A zone of maximum temperatures, reflecting the recent warm period, and a deeper zone of minimum temperatures, reflecting the earlier cold-snap, are apparent in the snow-cover.

Figure 14 provides information on conditions during the cold period which immediately followed the snowstorm. Curve 1 is the same as curve 6 of figure 13. Curve 2, for about 1450 Jan. 12, shows changes about 4 hours later (see fig. 6). Conditions then included: a) higher broken clouds (0.7 cover at about 5000 feet, 0.3 cover at about 1000 feet) in a clearing sky, b) no snowfall, c) no winds, d) falling air temperatures, e) return of a stable stratification, thus f) steeper vertical gradients, g) some unrest in the lower air layers, h) a cooling snow surface (because of radiation losses skyward, particularly to areas of clear sky), hence i) cooling in the upper layers of the snow-cover, as well as in the lowest air layers, but j) continued warming in the lowest layers of the snow-cover. Because of the influence of the clouds the cooling and consequent changes were not very rapid. Curve 3, for about 1730 Jan. 12, shows changes about 3 hours later (see fig. 6). Conditions then included: a) mostly clear skies (about 0.1 cover of high cirrus and alto-cumulus), b) no winds, c) ice fog, d) stable stratification with steep vertical temperature gradients (note 40 foot point), e) a sharp drop in temperature at the snow surface and an increased rate of cooling in the lower air and in the upper layers of snow, but f) continued warming in the lower layers of snow, and g) a lagging rate of temperature fall at the 40 foot level. This curve shows the sharply increased rate of cooling that typically follows the clearing of skies. It also shows the active part played by the snow surface. Curve 4, for about 2010 Jan. 12, shows changes

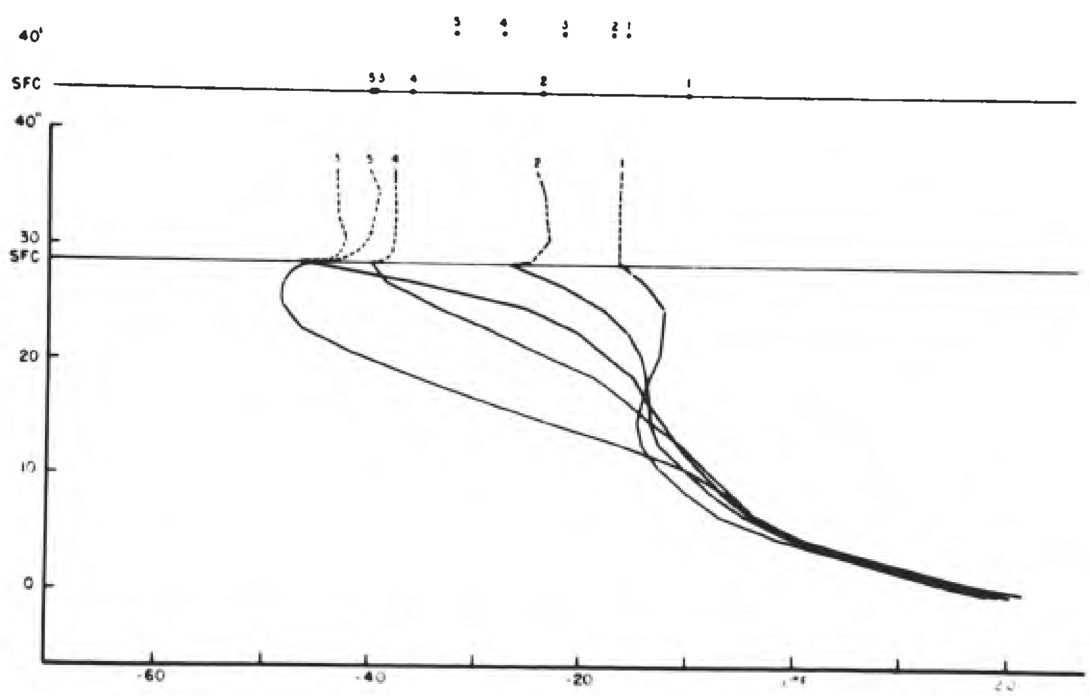


FIGURE 14

less than 3 hours later (see fig. 6). The conditions then included: a) an increase in high clouds (about 0.7 cover of high cirrostratus), b) light winds (about 4 m.p.h. at Ladd), c) no ice fog, primarily because of the winds, d) stability but less steep vertical temperature gradients, e) increased surface temperatures (because of winds and clouds) and higher temperatures in the lowest air layer, but continued temperature fall at the higher levels, and f) warming in the surface layers of the snow-cover, and continued warming in the lowest layers, but continued cooling in the upper layers (excepting the surface layers). This curve reflects the effects of a minor event of surface warming occurring during a general cooling period. Curve 5, for about 1050 Jan. 13, shows details at a time in the period of warming following the nocturnal coldest period (which resulted from rapid cooling following the return of clear, calm conditions near midnight - see fig. 6). Conditions then included: a) essentially clear skies (although cirrus clouds were arriving), b) no winds (though light winds soon followed), c) ice fog (which soon vanished), d) stability and steep gradients in the air, e) increased surface temperatures (because of diurnal heating in the general area and of the consequently warmer air), and f) warming in the upper layers of snow, but continued cooling further down, and little change in the lowest layers of the snow-cover. Much cooling of the snow-cover occurred during the nocturnal period of minimum temperatures. This curve shows the effects of diurnal heating superimposed upon the effects of continued cooling. At the time of the curve conditions favorable for a high rate of terrestrial radiation loss existed, but by the next hour an approaching snowstorm began to greatly alter these conditions.

Figure 15 shows changes occurring as the storm arrived. Curve 1 is the same as curve 5 of figure 14. Curve 2, for about 1700 Jan. 13, shows details above 6 hours later (see fig. 6). Conditions then included: a) a high thin overcast (lowering and thickening), b) no winds, c) no ice fog (though it soon returned, briefly), d) stability and steep gradients in the air, e) increased surface temperatures (representing a balance between the warming influences resulting from diurnal heating, including warmer air, and cooling influences, such as radiation losses to, and through, the cold high clouds as the daylight period ended and, a short time previously, to areas of clear sky), f) continued warming in the upper layers of snow and continued cooling in the lower layers, and g) temporarily little change in temperature of the lower layers of air (almost no change at Ladd for a period of over two hours centered on this time) as energy gains and losses temporarily balanced at the onset of night and before the storm brought a rapid rise. Curve 3, for about 1115 Jan. 14, shows details during the storm (see fig. 6). Conditions then included: a) a low overcast, b) no snowfall, c) no wind, d) little stability and slight vertical temperature gradients, e) in-

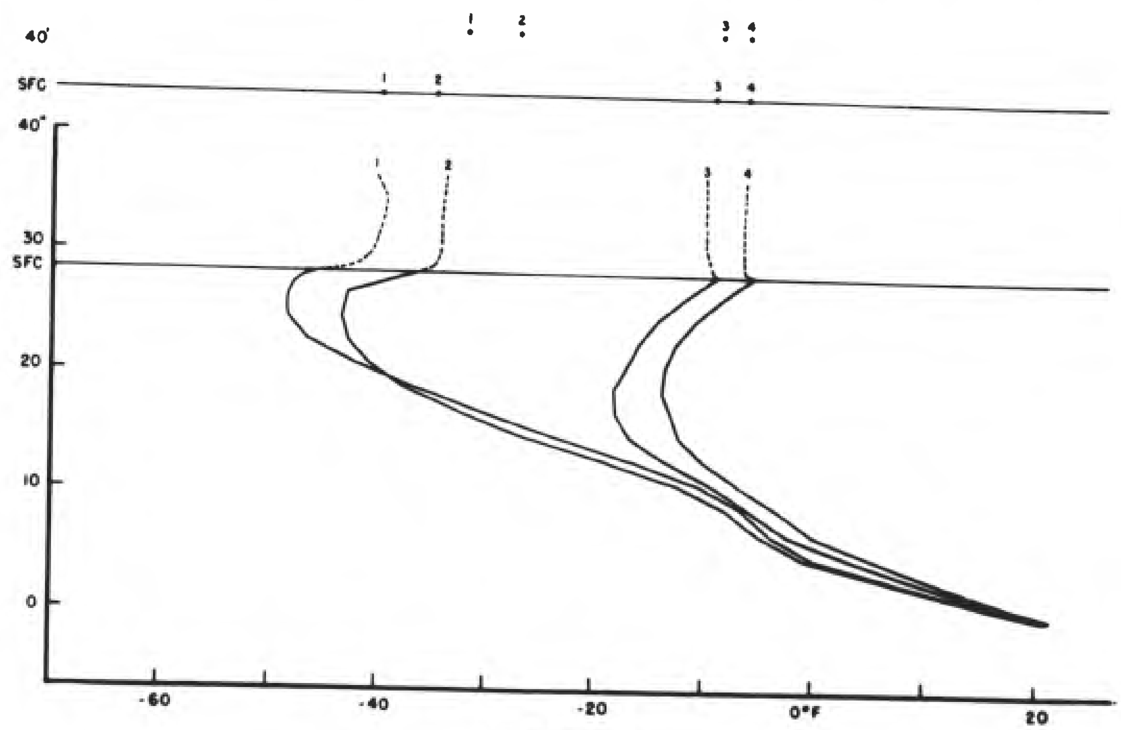


FIGURE 15

creased surface temperatures (because of radiation exchange with the warmer clouds) which precede slightly the temperature rises in the lowest air layers and uppermost snow layers, f) continued temperature rise throughout the air, and g) a temperature rise throughout the snow-cover (partly due to the penetration of long-wave radiation). Curve 4, for about 1820 Jan. 14, shows changes over 4 hours later (see fig. 6). Conditions then included: a) a somewhat higher but still low overcast, b) no snowfall (though snowfall began about 15 minutes later), c) no winds, d) isothermality, e) a temperature pattern similar to that of the last curve, and f) similar temperature increases in the air and in most of the snow-cover, with appreciable increases in even the lowest layers of the snow-cover. The last two curves show the effects of long-wave radiation exchange with the storm clouds, and of long-wave radiation penetration into the snow-cover (note that appreciable amounts of long-wave radiation may penetrate farther than 12 inches into the snow-cover).

Figure 16 shows a variety of situations. Curve 1 is the same as curve 4 of figure 15. Curve 2, for about 1415 Jan. 15, shows details during the period of partial clearing and cooling that occurred between the peaks of the multiple storm (see fig. 6). Conditions then included: a) thin high clouds covering most of the sky, b) no snowfall, c) no winds, d) increased stability and stratification following the brief period of surface cooling, leading to e) stagnation and a relatively dense accumulation of haze and smoke in the lower layers of air, f) unrest in the lowest layers of air, g) continued surface cooling (which was not rapid, because of the clouds), hence h) continued cooling in the lower air layers and in the upper layers of the snow-cover, but i) continued warming in the lower layers of the snow-cover. This curve shows the effects of a brief interval of moderate surface cooling, which was a result of partial clearing between storms. Curve 3, for about 1610 Jan. 16, shows details at the height of the major snowstorm (see fig. 6). Conditions then included: a) a low overcast, b) moderate snowfall, c) light winds (about 6 m.p.h. at Ladd) which began about noon, d) relatively high temperatures, e) approximate isothermality, f) an increased snow depth, g) snow surface temperatures little different from temperatures in the air above or in the snow just below (data missing for these thermocouple sets), h) continued warming in the lower air layers (actually just beginning to fall as colder air is advected into the region), and i) a marked increase in temperature throughout the snow-cover (to a large extent due to the penetration of long-wave radiation). The new snow, having fallen during a period of nearly constant temperature, forms an isothermal layer differing little in temperature from that of the snow as it fell. Some error due to effects of winds on the thermocouple lead wires is apparent in this curve. This curve shows an unseasonable warmth and an unusual uniformity of temperature. It represents conditions of a midwinter warm period,

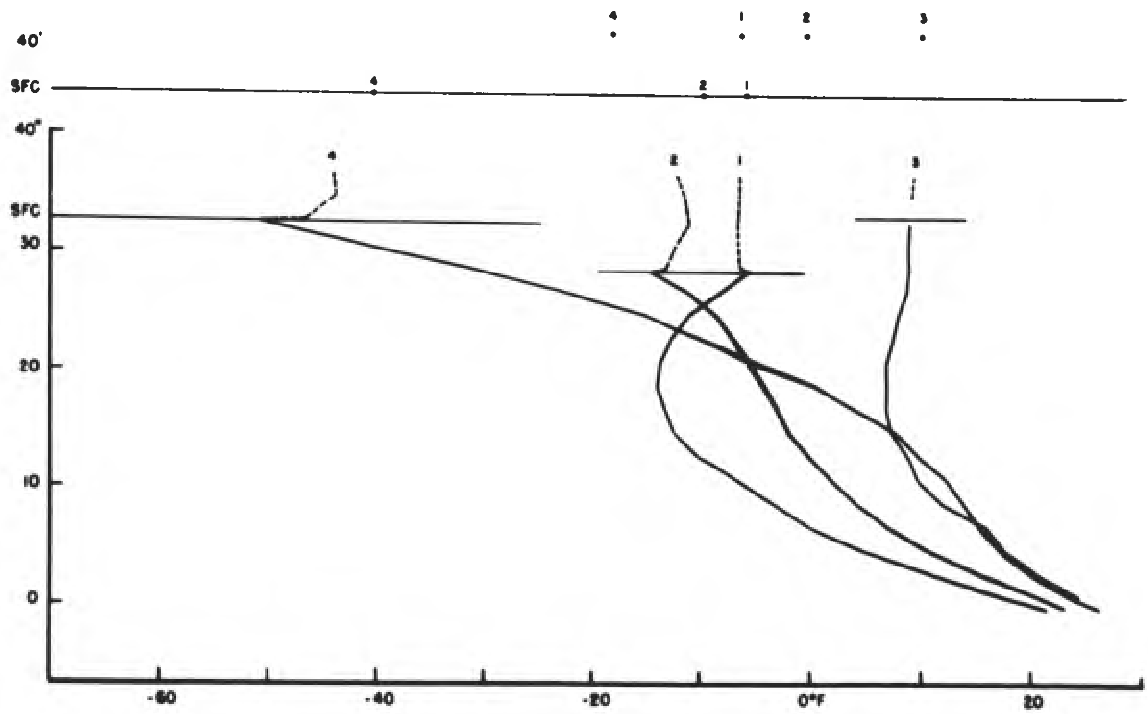


FIGURE 16

which is in a sense merely an interruption of a severe cold-snap (see fig. 3 and fig. 6). Curve 4, for about 1605 Jan. 17, shows changes about 24 hours later during the initial stages of the cold-snap which followed the storm (see fig. 6 and first points of fig. 10). Conditions then included: a) clear skies, b) temporarily no winds (in a period of light winds), c) no ice fog, d) stability and stratification, e) unusually steep vertical temperature gradients (see 40 foot point), f) unrest in the lowest air layers, g) continued rapid surface cooling, leading to h) rapid cooling of the lower layers of air, and i) marked cooling in the upper layers of snow (though some net warming has occurred at one deeper zone since the time of the previous curve), and j) a lag in the cooling in the higher layers of air. This curve reveals the extent of cooling taking place since the sky suddenly cleared about 10 hours earlier. It represents a time in the cold-snap stage of unsteady rapid temperature fall. This stage during this cold-snap was characterized by light to moderate winds (see fig. 10 and discussion on page 57).

Figure 17 shows conditions during the second severe cold-snap of the winter (see also figs. 3, 6, and 10). Curve 1 is the same as curve 4 of figure 16. Curve 2, for about 0920 Jan. 18, shows details at the time of a minor event of cooling during the unsteady early stage of the cold-snap (see fig. 10). Conditions then included: a) clear skies, b) variable light to moderate winds (8 to 10 m.p.h. at Ladd, considerably less at the lowest levels) which had just shifted direction (at the time of the temperature dip), c) no ice fog, d) a high degree of stability and stratification, e) a little unrest due to air motion in the lowest layers of air, f) very steep vertical temperature gradients in the air, g) low temperatures (at or near minimum) at the snow surface and in the lowest air layers, but warming in the lower air as a result of diurnal heating, and h) continued cooling at all levels in the snow-cover. This curve shows the effects of continued cooling of the snow-cover and air in the lowest zones, which were protected from the warming influences of the winds and also were relatively little affected by diurnal heating (up to this time). Curve 3, for about 1350 Jan. 18, shows details near the time of the peak of the period of diurnal heating (see fig. 10). Conditions then included: a) clear skies, b) persistent light to moderate east winds (5 to 9 m.p.h. at Ladd, a little less in the lower air layers), c) no ice fog, d) less stability and considerably less stratification, e) less steep vertical gradients, f) temperatures near maximum at the snow surface and in the lower layers of air, temperatures previously rising but soon to fall, g) appreciable settling of the snow-cover, h) considerable unrest in the lowest air layers, i) warming in the surface layers of snow (but a little subsequent cooling in the uppermost layer), and slight continued cooling in the lower layers, and

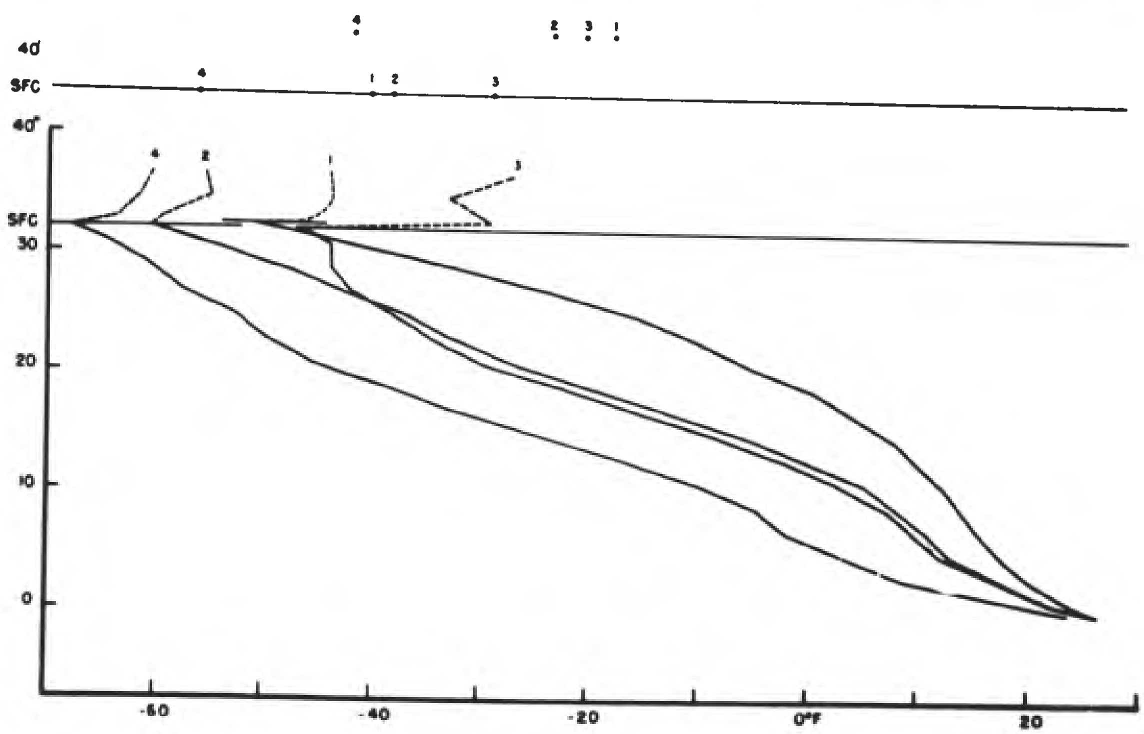


FIGURE 17

j) surface temperatures fluctuating with the varying balance of cooling influences (mainly radiation loss to the clear sky) and warming influences (largely effects of the winds, which brought warmer air into close contact with the surface, but also direct and other indirect effects of solar diurnal heating). This curve illustrates the effects of conflicting warming and cooling influences. Curve 4, for about 1030 Jan. 19, shows details just after the time of minimum temperatures, at the end of the period of rapid fall, following the cold-snap stage of unsteady fall (see fig. 10). Conditions then included: a) clear skies, b) no winds (light winds having stopped a few hours before), c) increasingly dense ice fog, d) a high degree of stability and stratification, e) relatively steep vertical temperature gradients in the lower layers of air, f) low but rising temperatures in the lower air layers, g) little unrest in the lowest air layers, h) snow surface temperatures near the minimum but rising, hence i) some warming in the surface layers of the snow-cover, but continued cooling throughout most of the snow-cover. This curve shows the effects of continued cooling in all microclimatic zones as the cold-snap continues.

Figure 18 shows conditions during later stages of the cold-snap, and during and after the subsequent windstorm. Curve 1 is the same as curve 4 of figure 17. Curve 2, for about 1740 Jan. 20, shows details following the period of diurnal heating on the coldest day of the cold-snap (see fig. 10). Conditions then included: a) clear skies, b) no winds in the lower layers of air (calm at Ladd), c) dense ice fog, d) a high degree of stability and stratification in the lower air, e) relatively steep vertical temperature gradients, f) steadiness in the lowest air layers, g) temperatures momentarily falling, after a minor event of warming, at the snow surface, in the upper layers of the snow-cover, and in the lower layers of the air (all zones at this time), and h) continued cooling in the lower layers of the snow-cover. This curve shows the effects of continued cooling in all zones, followed by a minor event of warming (diurnal heating), this followed by a brief period of cooling. The dashed lines deep in the snow-cover of this curve, the preceding curve, and several following curves, represent interpolations correcting significant convection errors, which occurred as the temperature gradients again became very steep in the lowest layers of snow. The errors resulted from the high degree of instability represented by the steep gradients and from the increased porosity of the lower layers of snow which was a consequence of prolonged recrystalization (metamorphosis). Curve 3, for about 0920 Jan. 21, shows details during the period of sharp temperature rise, shortly after the windstorm began to greatly affect the lowest layers of air (see fig. 10). Conditions then included: a) clear skies, b) moderate winds (10 to 15 m.p.h. at Ladd, somewhat less in the lower

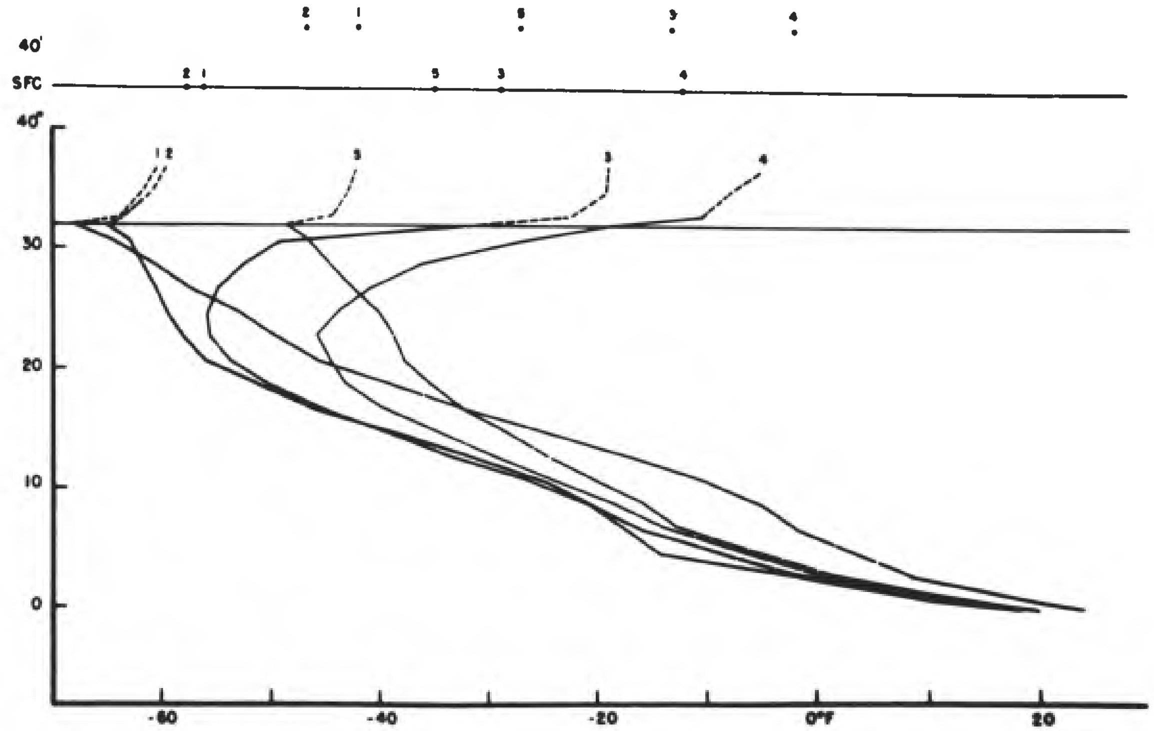


FIGURE 18

zones), c) no ice fog (which vanished when the surface winds arrived), d) less stability and little stratification, e) less steep vertical temperature gradients in the lower layers of air, f) rapidly rising temperatures in the air, g) considerable unrest in the lowest layers of air, h) rapidly rising snow surface temperatures, a consequence of the much warmer air blown onto and over the surface (see also BL data), hence i) rapid warming in the upper layers of the snow-cover, but j) little change in the lowest layers of the snow-cover (in sharp contrast to the situation when warming results from radiation exchange with clouds). This curve illustrates the effects of surface warming resulting from winds, winds which interrupted a cold period and mixed and blew away the shallow layers of very cold air. It shows unusually steep gradients near the upper snow surface, and shows a very cold zone remaining in the snow-cover. Curve 4, for about 1740 Jan. 21, an hour after the last point on fig. 10, shows details at a time near the peak of the windstorm (see fig. 6). Conditions then included: a) clear skies, b) moderate winds (10 to 20 m.p.h. at Ladd), c) no ice fog, d) some stability but little stratification, e) vertical temperature gradients in the air steep near the surface, but not steep in the higher layers, f) rising temperatures in the air, at the snow surface, and in the upper layers of the snow-cover, (following some large fluctuations), and g) continued warming in the intermediate and lower layers of the snow-cover. This curve shows the effects of continued warming due to wind action. A cold zone still persists in the snow-cover. Curve 5, for about 1035 Jan. 22, shows details just after the time of the night minimum after the windstorm (last point on fig. 6). Conditions then included: a) clear skies, b) no winds, c) ice fog, d) stability, stratification, and steep vertical temperature gradients in the lower layers of air, e) steadiness in the lowest layers of air, f) temperatures rising at the snow surface, in the uppermost layers of snow, and in the air (as a result of diurnal heating) following a period of continued fall, g) continued cooling in the upper layers of the snow-cover (excepting the uppermost layers), and continued warming in the lower layers of the snow-cover. This curve indicates a partial return to cold period conditions subsequent to the windstorm interruption.

Regular Periodic Events

Microclimatic conditions occurring during a period of relatively regular periodic diurnal variation are shown in figure 19. A comparable but somewhat more regular period, for February 1951, is shown in figure 7. Unfortunately, similarly detailed and complete data could not be obtained for this or the other periodic events of figure 7. The days shown in figure 19 were not entirely comparable, because of minor event differences, but

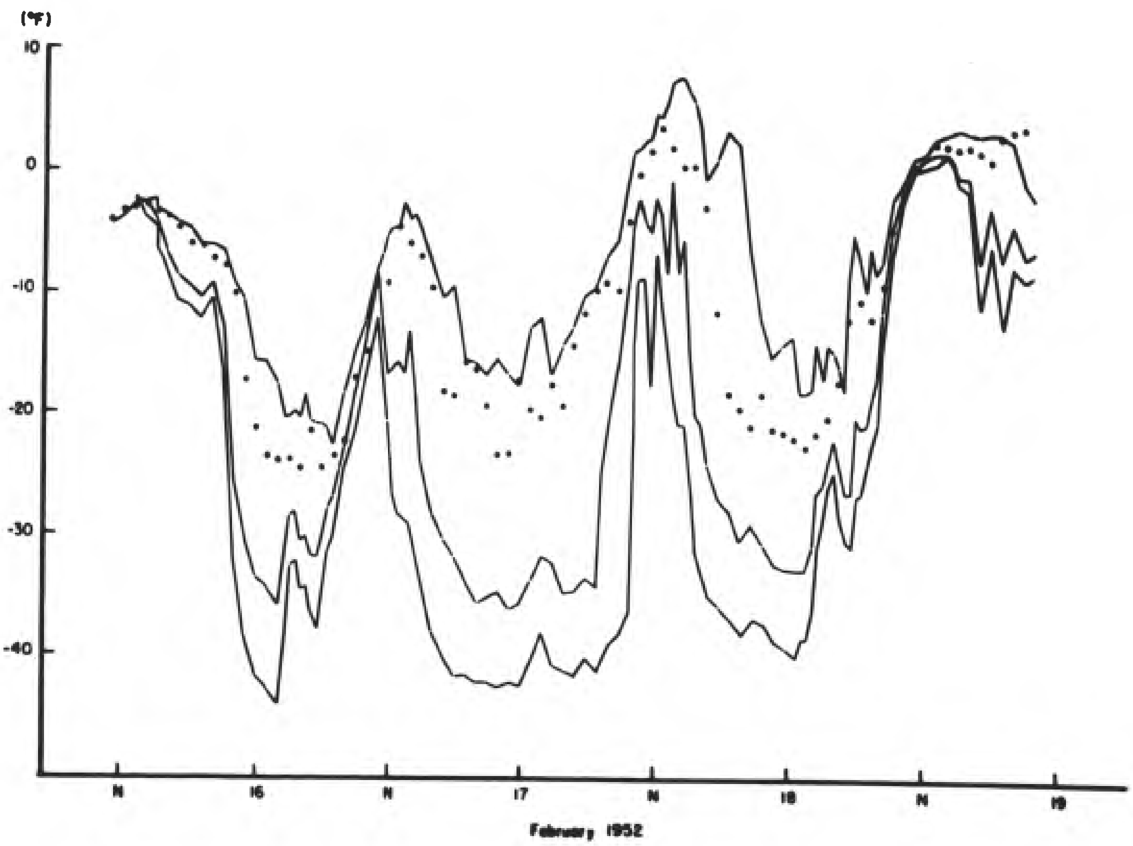


FIGURE 19

even so this sequence represents a good example of a regular periodic event. The curves are: 1) lowest for the snow surface at the station SD, 2) medium for the snow surface at the station BL, 3) highest for the air at the 40 foot level at the station BL, and 4) dots for Ladd. The sequence of events depicted was roughly: a) a snowstorm on February 15, b) clearing then clear skies near midnight and early morning of February 16, c) increasing cloudiness, almost becoming overcast near noon February 16, d) clearing soon after noon February 16 (and remaining clear or essentially clear February 17), e) winds beginning near midnight February 16 and continuing (with speeds 2 to 13 m.p.h. at Ladd) through February 17, f) clear and windless near midnight and early morning hours of February 18, g) occasional light winds February 18, h) increasing cloudiness on February 18 becoming overcast by noon, i) some clearing midnight February 18, and j) a light snow at midnight and during the early morning of February 19. Thus the period commenced after a snowstorm and ended with a snowstorm. The first diurnal peak reflects clouds but no winds, while the second reflects winds but no clouds; both influences amplify the normal peak due to diurnal heating. Minor events account for the other differences. Clearly shown are: a) the isothermality during snowstorms and heavily clouded periods, b) fluctuations characteristic of windy periods, c) rapid cooling during periods of clear skies, the cooling proceeding at an ever decreasing rate, d) steep vertical temperature gradients in the air during periods of cooling, especially during the earlier stages of cooling (before a deep zone of cold air is formed near the surface - compare figs. 9 and 10), e) the still steeper gradient occurring when the lowest layers of air are protected from winds (see also fig. 10), f) the persistence of vertical gradients in the air during the windy period, and g) the suddenness and steepness of temperature rises and falls in response to the influences of clouds, clearing, insolation, and winds.

Figure 20 presents details of conditions in several microclimatic zones at various times during this compound event. Curve 1, for about 1410 February 15, shows details at a time near the peak of the preceding snowstorm (see fig. 19). Conditions then included: a) a low overcast, but thin spots and breaks beginning to appear, b) moderate snowfall, c) no winds, but appreciable air movement in the higher zones, d) relatively high temperatures and approximate isothermality in the lower layers of air, though a little cooling is apparent in the lowest layers, e) unsteady conditions in the lowest layers of air as a result of f) a slight amount of cooling at the snow surface (as the clouds lift, thin, and begin to break), and g) generally warm conditions within the snow-cover, the surface layers cooling a little. Curve 2, for about 1440 February 16, shows details a little after

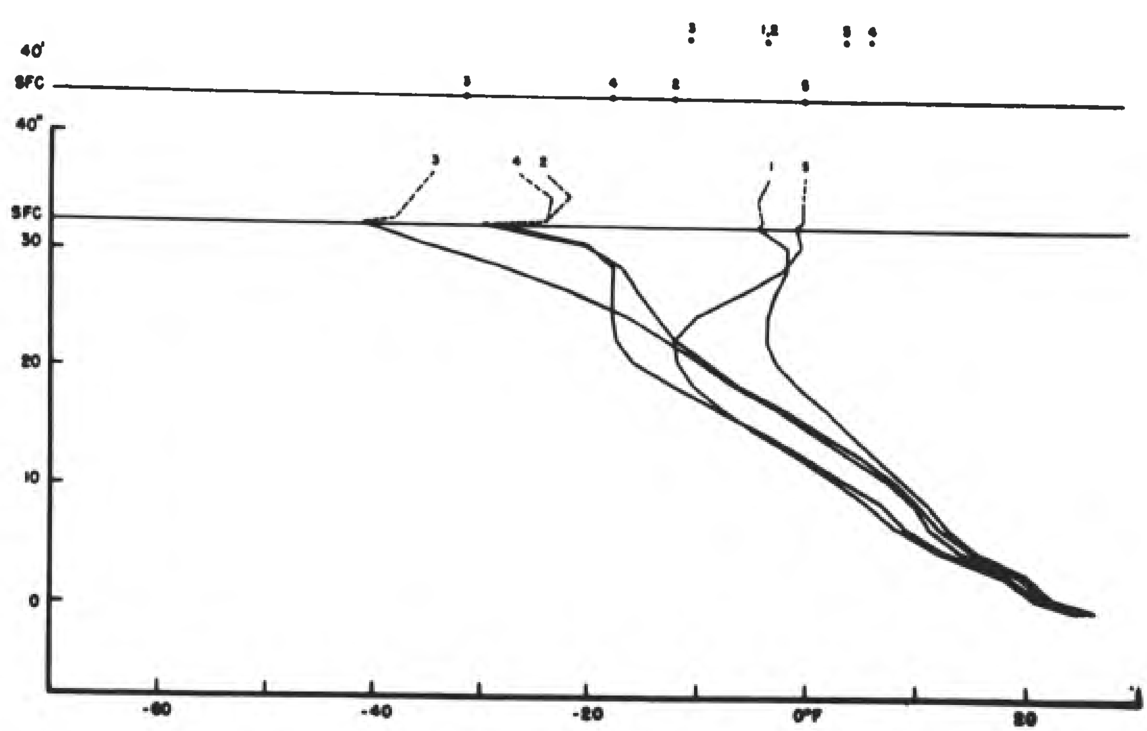


FIGURE 20

the midday peak (see fig. 19). Conditions then included: a) clear skies, b) no winds, but some drift, and unrest in the lowest layers, c) haze (preceding a little ice-fog), d) stability, stratification, and steep vertical temperature gradients in the lower air layers, e) falling temperatures, falling rapidly in the lowest layers of air, lagging somewhat at higher levels, and f) snow temperatures showing effects of cooling in the upper layers during the previous night, followed by diurnal warming, and after that cooling, and showing continued cooling in the lower layers. This curve shows the effects of the last two cooling and warming events, and of the current cooling event. Curve 3, for about 1750 February 16, shows changes about 3 hours later (see fig. 19). Conditions then included: a) clear skies, b) no winds, but some drift (soon to become temporary light winds), c) increased stability and stratification, d) steeper vertical temperature gradients in the lower layers of air, f) rapidly falling temperatures at the snow surface, in the upper layers of snow, and in the lowest layers of air (but near the end of the fall at the SD surface - see fig. 19), g) slower fall at the higher levels, and h) continued cooling throughout the snow-cover. The non-linearity of the gradients in the lowest layers of snow is largely due to convection within these layers. This curve shows the consequences of continued cooling in all of the zones. Curve 4, for about 1615 February 17, shows details at a time just after the second diurnal peak (see fig. 19). Conditions then included: a) clear skies overhead (a little cirrus to the far southwest), b) light winds (3 m.p.h. at Ladd), c) a high degree of stability and stratification, d) steep vertical temperature gradients in the lower layers of air, e) falling temperatures in the air and at the snow surface (at the start of a sharp drop at the higher levels, but nearing the end of a sharp drop at the SD surface - see fig. 19), f) unrest in the lowest layers, and g) snow temperatures showing in the upper layers the effects of continued cooling the previous night, followed by diurnal heating, and then renewed cooling, and showing continued cooling in the lower layers. This curve shows effects similar to those shown by curve 2. Curve 5, for about 1640 February 18, shows details at a time during the second snowstorm (see fig. 19). Conditions then included: a) an overcast (at about 6000 feet) soon breaking temporarily, b) no snowfall (a very light fall began several hours later), c) no winds (though light variable winds occurred soon afterward), d) little stability or stratification, e) slight vertical temperature gradients in the lowest layers and reduced ones in the higher layers, f) air temperatures relatively high and falling a little (as clouds break somewhat), after a period of marked rise, g) strong evaporation at the snow surface, h) a little cooling at the snow surface, but i) continued warming in the upper layers of the snow-cover (except in the surface layers), and continued cooling in the lower layers. This is a relatively complex curve, and shows the effects of two recent major events and one or more current minor events. It shows well the warming effects of a period of clouds following a cloudless minor cold period. These few curves hardly suffice to show the changing structure of conditions during an event as complex as this one. However they do reveal the nature of the major features. Time limitations prohibit the presentation here of more details.

Late Winter Cold Periods. As the season progresses cold periods become fewer and less cold, but occasionally one develops into a respectable even if short lived truly cold period. Figure 21 shows a sequence of events including such a late winter cold period (see also fig. 3). In this the curves are the same as in figures 10 and 19. The sequence of events during this period was roughly: a) rising temperature on March 4, as storm clouds arrive and lower, and winds continue light to moderate, b) snowfall in the afternoon of March 4 continuing to about noon March 5 (broken lines indicate buried surface thermocouples), c) overcast to broken clouds at varying heights, weakening winds, and some cooling during the morning of March 5, d) movement eastward of a solid layer of clouds, followed by clear skies, the edge passing overhead a little after noon, e) a sharp drop of temperature, particularly in the low areas, as the clear skies arrive and persist, f) essentially no winds from noon of March 5 to March 7 (only drift, occasionally briefly becoming light winds), g) the return of broken high and middle clouds at about 0700 March 6, increasing and lowering after that and combining with diurnal heating to break the cold period and dissipate the cold air, and h) some clearing in the afternoon of March 6, followed by lowering and increasing of clouds (almost to an overcast) in the late evening

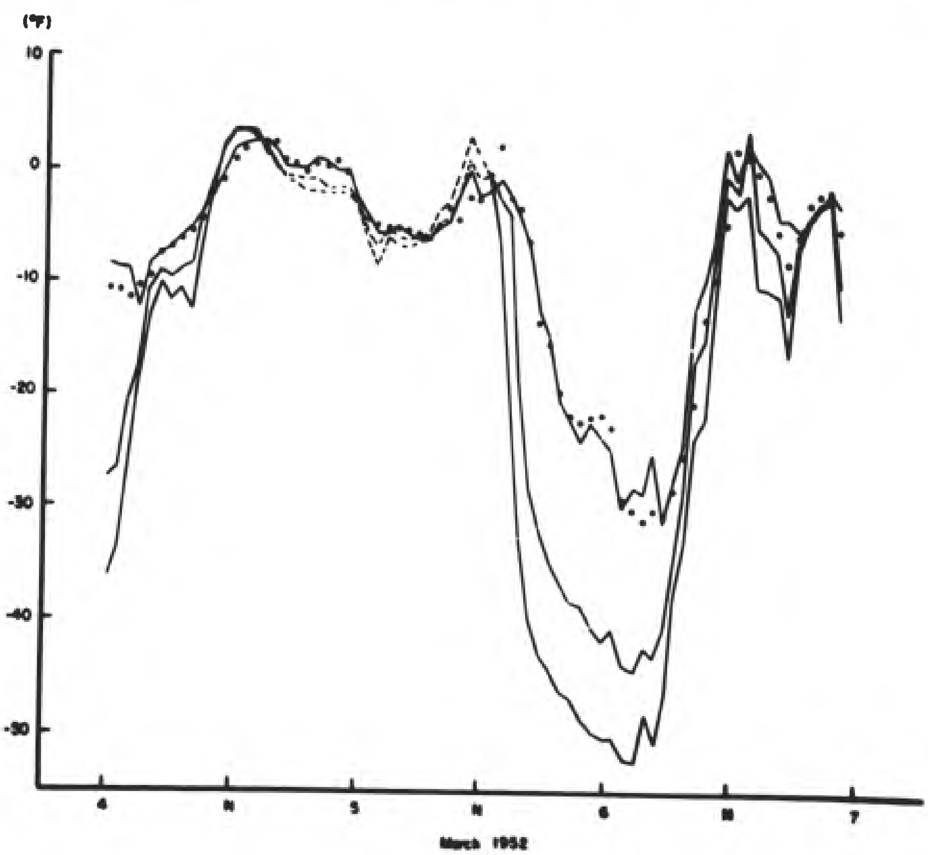


FIGURE 21

of March 6. The cold period curves reveal: a) the rapid cooling following clearing, cooling proceeding at an ever decreasing rate, b) the lag in cooling at higher levels, c) the steep vertical temperature gradients in the air at the several stages of development of the cold period, d) the minimum temperature typically occurring in the morning, e) a minor peak near the time of minimum temperatures, representing a brief occurrence of light winds (4 m.p.h. at Ladd) during an otherwise essentially calm period, and f) the rapid break-up as clouds and sunlight return. The protected low zones show less fluctuation due to air motion then the higher zones. Some fog occurred at the time of the temperature minimum.

Additional details of microclimatic conditions during this sequence of events are presented in figure 22. Curve 1, for about 1410 March 4, shows details at a time of the snowstorm after the temperature peak and a little before the snow began to fall (see fig. 21). Conditions then included: a) an overcast (at about 6000 feet), b) no winds temporarily (in a period of light winds), c) some cooling at the snow surface, in the surface layers of snow, and in the lowest air layers, shortly following warming in these zones, d) approximate isothermality in the air layers, and e) generally high snow temperatures showing the effects of cooling, then heating, then cooling again. Curve 2, for about 1445 March 5, shows details at the start of the rapid temperature fall (see fig. 21). Conditions then included: a) almost clear skies (edge of cloud bank far to east), b) no winds, but some drift, c) air temperatures relatively high but falling rapidly (in lowest zones) or about to fall rapidly (in higher zones), d) increasing stability and vertical temperature gradients, e) unsteadiness in the lowest air layers, f) rapid cooling at the snow surface and in the surface layers of snow, and g) effects of continued warming deeper in the snow. At the time of this curve the rapid cooling had just commenced. Curve 3, for about 1605 March 5, shows conditions an hour and 20 minutes later (see fig. 21). Conditions then included: a) clear skies overhead, b) no winds, c) rapidly falling temperatures in the air, d) much increased stability, stratification, and steep vertical temperature gradients in the lower layers of air, e) very rapid cooling at the snow surface, and in the uppermost layers of snow, but f) little change in the lower layers of the snow-cover. This curve reveals the rapidity of cooling in the uppermost layers of snow. Unfortunately, no complete curve is available for the time of the minimum temperatures. Curve 4, for about 1010 March 6, shows details at a time during the temperature rise when a little over half of the rise had occurred (see fig. 21). Conditions then included: a) high cirrus clouds (about 0.6 cover) and some lower alto-cumulus (about 0.2 cover), forming in effect a high thin overcast, b) no winds, c) temperatures

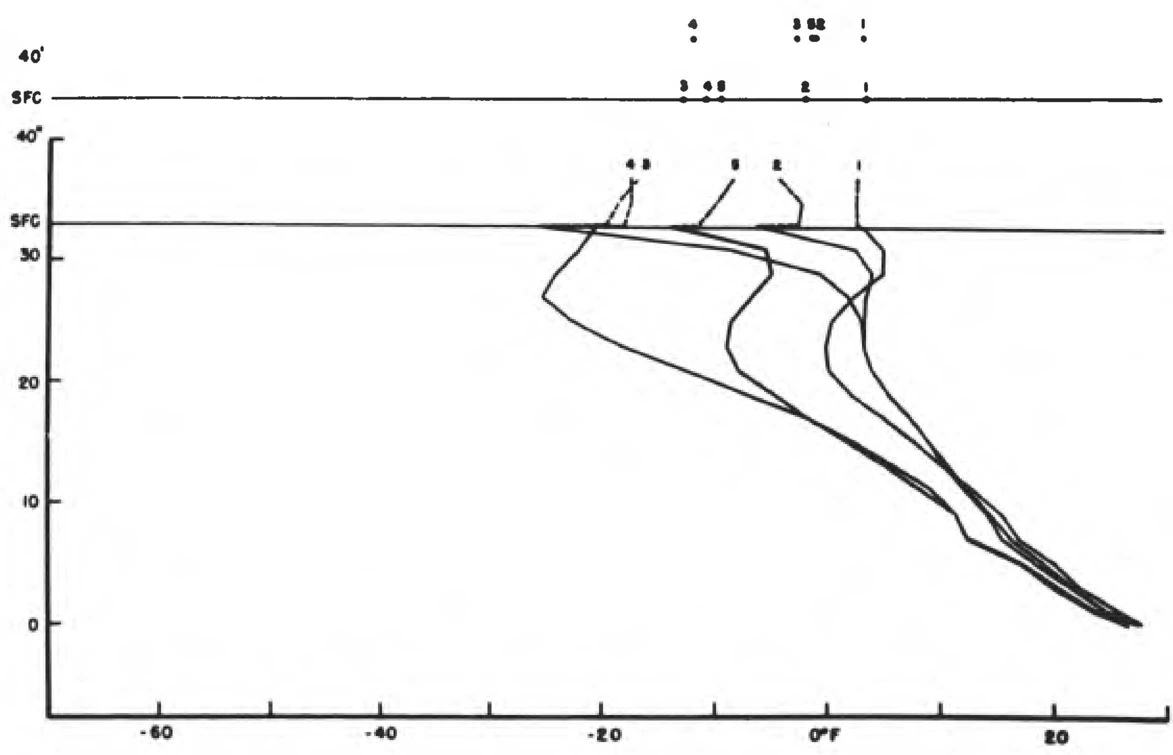


FIGURE 22

rising rapidly in the air, at the snow surface, and in the upper layers of the snow-cover (partly because of penetration of long-wave radiation) d) decreased stability and vertical temperature gradients in the lower layers of air, e) unrest in the lowest air layers, and f) snow temperatures showing the effects of much cooling in the upper layers of the snow-cover, and cooling in the other upper layers of the snow-cover, and of continued cooling in the lower layers. This curve shows the effects of pronounced cooling followed by rapid surface warming due to clouds (and sunlight). Curve 5, the last, for about 1050 March 6, shows conditions at a time during the minor period of cooling after the peak of the period of warming (see fig. 21). Conditions then included: a) partly cloudy skies (almost a thin overcast of high clouds), b) no winds, but some drift, c) temperatures falling at the snow surface and in the air, d) increased stability and vertical temperature gradients in the lower air layers, and e) snow temperatures showing rapid cooling in the surface layers, continued warming in the upper layers (excepting the surface layers), and continued cooling in the lower layers. This curve shows the effects of a minor event of cooling, following major events of cooling and warming. The non-linearities and fluctuations of conditions in the lowest layers of the snow-cover are largely due to convection within the porous lowest layers. By this time the porosity was a little greater about the thermocouple set than it was in the adjacent undisturbed snow-cover, but still was less than the natural porosity (due to recrystallization) about slender twigs and stems.

Other Phenomena

In addition to the conditions considered above many other phenomena of the physical environment are at times of considerable importance to the resident mammals and birds. Of the many that merit it only a few can be given special consideration here. These important geophysical phenomena include:

Permafrost. Permafrost or permanently frozen ground is found in most of the areas of the continental interior of Alaska, and almost everywhere on the Arctic Slope. Fairbanks is on the edge of the zone of permafrost, so that both permanently frozen ground and ground not permanently frozen are to be found in the vicinity. In suitable locations, such as shaded areas, permafrost is found considerably farther south as well; while in unfavorable situations, such as some unshaded south-facing slopes of hills and zones close to large bodies of water, it may be absent considerably farther north. Permafrost consists of all materials of the ground which permanently have a temperature below 32°F. Thus it may be dry (as in dry sand) or wet (in wet zones with a lowered freezing point), may contain little frozen water or a great deal (over 80%), and may be relatively cold (as in certain zones in the far north) or relatively warm (as near Fairbanks, where it usually has a temperature just below freezing). Non-permafrost zones (talik) may lie within it. Above it lies the "active layer," the zone seasonally thawed, which is commonly several feet deep near Fairbanks, but is often less than a foot deep on the Arctic Slope. The active layer includes the coldest zones of the ground during the winter. In this research in the continental interior of Alaska little distinction was made between permafrost and frozen active layer. Most of the observations on conditions in the soil refer to the frozen active layer. However stations and observational areas were over both permafrost areas and areas without permafrost, and a variety of frozen ground phenomena were observed (most of only minor importance to animals).

In the vicinity of the river much of the ground was of a dry sandy type, little different in characteristics when colder than 32°F (as in the first several feet of soil) or when warmer than 32°F (as near the surface at exposed and sunlit areas). On the Arctic Slope permafrost was of considerable importance (see also page 103). Since phenomena of the frozen ground are numerous and complex, for further details the reader is referred to Muller's text (31) and other works such as (6, 7, 8, 10, 13, 24, 34, 45, 48, and 49).

Subnivean Air Spaces. Because of the persistent steep temperature gradients in the lower layers of the snow-cover, and because the air in the spaces between ice grains of the snow-cover is usually close to saturation (with respect to ice), steep saturation water vapor gradients also persist in the lower layers of the snow-cover. These lead to a continuous migration of water vapor upwards, and the formation of increasingly large air spaces at the base of the snow-cover. As a result of the large amount of recrystallization occurring in the lower layers of the snow-cover the layers came to be composed of large, coarse-granular ice crystals or depth-hoar. While the lower boundary of this very loose, coarse-granular snow remains very ragged and poorly defined, the growing space beneath it widens to an average width of about 0.5 to 1 inch, or even more, by late winter under undisturbed snow-cover one to two (or more) feet in depth. The spaces are, in effect, commonly even wider, partly because of holes and gaps along and under vegetation, and partly because of the wanderings of small mammals. Even where the depth-hoar extends to the soil surface it does not hinder the small mammals significantly, for they may easily brush it aside as they move about and seek food. The snow is supported above the extensive subnivean air spaces primarily by vegetation and its own coherence. When the support becomes inadequate the snow-cover falls or sags to the soil surface. A conspicuous collapse appears to happen only rarely under natural conditions, but may occur commonly in snow-cover over which one is skiing or snowshoeing (see fig. 23).

Ventilation. The air in and under the snow-cover appeared to be relatively stagnant. However the enclosed air appeared to be fresh enough for suffocation not to be a danger, probably largely because of the porosity of the snow and the holes caused by penetrating vegetation. In areas with many holes to the surface appreciable amounts of dense cold air did sink down to the lower layers to thus cause colder subnivean zones. During periods of warming and of falling pressures some expanding air may have left the snow-cover, while during periods of intense cooling and of rising pressures some air may have entered the snow-cover. The importance of such effects is unknown. Occasionally, for reasons not known, a considerable amount of warm air may rise from the zone at the base of

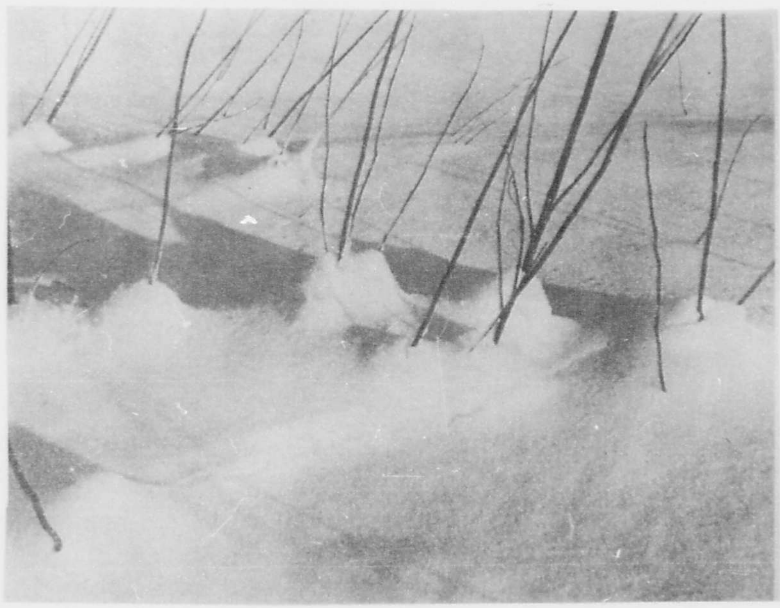


FIGURE 23

the snow in an area with penetrating holes. Figure 24 shows the effects of such an outflow, which occurred from the holes at the base of a bush. Cooling of the warm, saturated subnivean air led to the extensive frost formations shown. Such vents represent local warm zones, with unusually warm conditions in the upper layers of the snow-cover.

Cold pockets and warm pockets. Conditions in depressions and channels cut into the floor of the valley lowland were always colder, when clouds were few or absent, than the conditions over the valley lowland. In such low area cold pockets dense, cold air accumulated and stratified, the coldest and most dense air coming to lie lowermost. There protected from light winds, and often protected from solar radiation by shade pro-

FIGURE 24

ducing vegetation and topography, the cold air layers usually stagnated and persisted long after the coldest layers were dissipated at the higher areas. The coldness attained appeared to be greatest in the deeper cold pockets with the greatest ratio of cooling surface to volume of contained air. Similar but less extreme cold conditions formed in the small scale dents, depressions, and channels of the upper surface of the snow-cover.

Warm pockets occurred commonly during the daytime when clouds were few, especially later in the season when the sun was higher and the days were longer, in areas backed by south-facing slopes, walls, or surfaces. Surprisingly warm conditions, and often thawing, occurred at south-facing hollows, channels, banks, and other structures (including tree trunks, logs, and brush). The heating was due primarily to absorption of solar radiation, especially at snowless surfaces of vegetation and soil (as at steep banks), often combined with reflection of solar radiation from snow covered slopes and surfaces (reflector-oven effect). The prevailing calm conditions and the slowness with which the heated air layers escaped were also important factors.

Drainage. During periods of rapid or continued cooling moving masses or streams of air colder and more dense than the adjacent air commonly moved down slopes, gullies, and channels. Such cold air drainage contributed to the air motions of the generally windless colder periods, and sometimes formed appreciable winds. In some places near mountains, as near Big Delta, Alaska, such katabatic winds were strong and persistent and caused markedly modified climates. Near Fairbanks the drainage was usually too weak to qualify as winds. However, in the channel of the Chena River the downward drift or flow of dense cold air was commonly appreciable and occasionally amounted to a light wind. There it undoubtedly decreased the temperature fall and coldness attained by the lowest layers of air, which were rarely so cold as the stagnant lowest layers in the nearby depressions. Drainage down the channel of the Colville River at Umiat, Alaska, was a very important component of the midwinter conditions observed there.

Ice Fog. The conditions of "ice fog" (of suspended, very fine ice crystals) and of "ice crystals" (of slowly falling, larger, more highly oriented ice crystals) are in many respects simple cirrus clouds at and near the earth's surface. They occur only during the cold periods when winds are weak or "calm", and are confined to the cold lower layers of air. Ice fogs may become exceedingly dense in the vicinity of settlements during cold-snaps when combustion and other sources put much water vapor into the stagnant lower layers of air. They reduce visibility, and reduce incoming solar radiation, hence increase the winter darkness and reduce diurnal heating. They also reduce long-wave terrestrial radiation losses, hence tend to retard radiational cooling. In this research they affected the valley lowland areas and stations, but rarely if ever affected the Birch Hill station.

Hump and Hollow Topography. The microclimatic conditions at small topographical ridges, rises, and humps (with dimensions of the order of a few to a few tens of feet) were often quite different from those at small channels, depressions, and hollows (of similar dimensions) nearby and in the same type of area. The humps were more exposed to drainage air and motions and winds. At humps the snow-cover tended to be somewhat more shallow and also more disturbed (blown away, drifted, or compacted) by winds. At humps, more of the "surface" (relative to the mass involved) was exposed to the sky, and lost heat because of steep outward thermal gradients. Furthermore the humps were usually farther from the upper relatively warm zones of the ground in general. As a consequence temperatures in the zone at the base of the snow-cover and in the uppermost levels of the soil were usually markedly lower at humps than at hollows.

In contrast, the hollows were often more protected from air drainage and winds, often containing, and instead being affected by, a relatively stagnant body of dense cold air. At hollows the snow-cover tended to be deeper and little affected by winds (except when winds blew in additional snow). Although the "surface" was commonly exposed to considerably colder air, and thus lost heat over steeper outward thermal gradients, this concave "surface" was more closely surrounded by warm earth (and sometimes water), and was set deeper into the earth hence closer to the upper warm zones of the ground. As a consequence at hollows the temperatures of the zone at the base of the snow-cover, and of the upper layers of the soil were usually considerably higher than those of the corresponding zones at humps. During the coldest periods the highest temperatures found in zones at the base of the snow-cover, at the soil surface, and in the upper layers of the soil (where those zones were not affected by man) were found at the bottom areas of relatively deep depressions. This was so despite the fact that the coldest conditions found during the same coldest periods were found at the same bottom areas of the same depressions (but in the zones at and near the upper snow surface). The most cold-sensitive small mammals studied typically confined their activities to the warmest subnivean zones of such depressions, and apparently rarely or never went into the corresponding zones of nearby humps.

Wind-Chill. Coldness, as the word is used in this paper, means lowness of temperature. It reflects the effects of low values in zones of the temperature fields (ambient temperatures) and of low effective surface temperatures (radiation temperatures). It is a rough measure of rates of energy loss. Since drift, drainage air motions, and winds also contribute to the rates of energy loss, hence to the subjective feeling and practical importance of "coldness", another term wind-chill is commonly used for the "coldness" (that part of the total cooling) due to the action of the winds and the other air motions. The wind-chill, for example, is approximately the same when the wind is 2 m.p.h. and the temperature is -40°F, as when the wind is 5 m.p.h. and the temperature is -20°F, or when the wind is 13 m.p.h. and the temperature is 0°F (this degree of wind-chill is the limit above which exposed flesh can be expected to freeze) (33, 44). During the calm, cold conditions of midwinter, at areas of the continental interior, and in the various windless microclimatic zones, the degree of the wind-chill was relatively high in the cold zones and low in the warm zones, but was considerably less than it would have been if winds had been present. However during windy periods, at windy areas of the continental interior (as at Big Delta, Alaska), on the Arctic Slope, especially at the Arctic Coast, and on the Arctic Ocean the degree of the wind-chill was often as high or (especially in the cold zones) even considerably higher even though the temperatures at such times and places were usually higher (sometimes markedly higher). The worst conditions, extremely low temperatures combined with strong winds, were not encountered during these studies. Such conditions are exceptional at the earth's surface, occurring at only a few special places and under special circumstances (as at high mountains, including Mt. Washington, New Hampshire, in the high Arctic and Antarctic, and where fall-winds gain appreciable strength but still remain cold).

Environmental Conditions on the Arctic Slope

The winter conditions, both geophysical and meteorological, on the Arctic Slope of Alaska, and particularly on the Arctic Coastal Plain and along the Arctic Coast, were in general quite different from the corresponding conditions of areas, such as the Fairbanks area, in the continental interior of Alaska. The frozen Arctic Ocean had an important warming influence upon the lower layers of air. While some of the warming was due to the conduction of heat through the ice and snow, and some was due to heat added over areas of open water (which were caused by the action of winds on the ice), much was due to the mixing action of the winds, which swept unhindered over the vast flat areas of the Arctic Ocean (and also over the flat Arctic Coastal Plain).

On the Coast when the common winds from ocean to land occur these more moderate conditions prevail over the coastal areas, despite the higher latitude, longer nights, and consequent potentially greater radiation losses. It should be noted that the moderateness of the conditions refers primarily to the temperatures. Because of the persistent moderate to strong winds the wind-chill conditions may be severe, even more severe than those at the colder interior areas. When open leads occur near the shore conditions of fog, low stratus clouds, and light snowfall commonly occur. Other types of cloudiness are not uncommon and effectively reduce the surface cooling. Storms affecting the continental interior may also affect these more northern areas.

In contrast when the winds blow from land to ocean the colder air moving in from areas farther inland brings lower temperatures. When clear skies prevail and winds are weak, as when an anticyclone dominates the regional atmospheric circulation, the temperatures may fall very low. Then true cold-snap conditions may occur. Such cold-snaps however are usually not as cold as those developing over the continental interior. The common cloudiness and winds tend to reduce the coldness of these advectional and radiational cold periods.

The winds are one of the most striking winter characteristics of the coastal plain and coastal areas. Little retarded by the strikingly flat tundra, or by the somewhat more rough but also very flat frozen ocean, winds sweep these areas almost continuously. They commonly blow for days at a time, and in strength, from approximately the same direction and with little change in strength. As a consequence the lower layers of air are commonly well mixed, hence considerably warmer than the lower layers of air of areas in the continental interior where calm, cold conditions prevail. Also the snow-cover is greatly disturbed. Little snow remains where it falls. Most of it lies in hard-packed drifts, and forms a snow-cover of highly variable distribution and depth. The small local heights and humps commonly have little or no snow, while the low areas, hollows, and lee slopes all have drifts, which may be only a few inches in depth or may have a depth of many feet.

Thus by redistributing the snow the winds tended to level the terrain. However by causing sastrugi (rough, hard ridges of drifted snow) they also roughened level areas. Many of the drifts were migratory, slowly eroding on one side, reforming on the other, and thus moving along the ground. Others associated with lee slopes or hollows, were semi-permanent, remaining in one place throughout the winter, and sometimes becoming quite large. While most of the snow-cover moved about in response to the winds, snow protected by rime or glaze crusts (as caused by wind blown fogs) usually did not. Wherever the snow remained in place for long periods of time, as under crusts or at the semi-permanent drifts, depth-hoar developed much as it did at continental interior areas. Blowing snow was an important phenomenon per se, and at times was as much of a hazard as the cold or the wind.

As a consequence of the factors and influences listed above and others, the conditions along the Arctic Coast of Alaska differ from those of the interior by having typically: 1) a smaller range of temperatures, more moderate winter temperatures, and smaller fluctuations; 2) a lower annual average temperature, and generally lower temperatures at the ground surface (and also to some depth into the ground); 3) a very low total precipitation but frequent light falls of snow which accumulate in drifts over a long winter period; 4) a higher frequency and degree of cloudiness, and in some areas also an increased frequency of fogs; 5) a snow-cover of a totally different nature -- of highly variable depth, low average depth, and relatively low insulating value; 6) persistent strong winds which usually prevent the development of distinct microclimates in the lower layers of air; 7) comparatively sudden changes in conditions when the winds change in trajectory or component from offshore to onshore or vice versa.

Deep and relatively cold permafrost underlay the area; and phenomena of the frozen ground were common, of many types, and often conspicuous. Several of these were of particular importance to the local animals. Areas of "high-center polygonal ground" formed zones of rough topography, which often acquired relatively extensive, deep, interconnected semi-permanent snowdrifts. The "high-center polygonal ground" consisted of areas broken up into a series of segments, roughly polygonal in outline, each of which was a type of hump. The humps were commonly several feet high and several feet in diameter, had convex generally dry (often xeric) tops, and were surrounded by channels of low, mesic (sometimes wet) areas, which often had a good growth of low vegetation. Lichens and mosses grew on the tops; grasses, sedges, low growing higher plants and others grew in the hollows and channels (49). Vertical ice wedges lay under the hollows and channels. Areas of "low-center polygonal ground" formed zones of rather flat terrain, which often had only a shallow, transitory snow-cover. They consisted of areas divided into large segments, polygonal in outline, which were often quite regular, sometimes strikingly so. The segments were of slight height (at the margins), were commonly tens of feet in diameter, had shallow depressions at their centers, and were separated by channels or grooves. The low center was commonly wet (in the warm season), as were also the channels. Vertical wedges of ice lay under the channels. Both types of polygonal ground varied considerably. Because of the many intermediate formations found they are sometimes considered to be stages of a developmental sequence.

Above the snow and ground surface microclimates as distinct as those observed at areas in the continental interior were generally lacking. At times, close to the surface, particularly when winds were weak or absent and skies were clear, microclimatic conditions did occur. But when the winds blew these became essentially all the same and the same as the conditions of the macroclimate. In the snow and in the soil, however, distinct microclimates and microclimatic zones did normally occur. Where the snow-cover was thin or absent the surface layers of the soil often became very cold. But where the snow remained deep, as at the larger semi-permanent drifts (at banks, bluffs, drainage channels, and at areas of high-center polygonal ground), relatively warm subnivean microclimates could be found. At one place, under a four-foot drift subnivean temperatures of 16°F were measured, at a time shortly after a cold-snap when many areas had subnivean temperatures of 0 to -10°F, and the air temperature was about 0°F (representing a minor peak).

Inland, at Umiat, the conditions observed were intermediate between those of areas near the coast and those of areas across the Brooks Range and in the continental interior. There winds were often weak, but also were commonly strong. The snow was deeper, in places deep and soft, but in others shallow, drifted, or hard-packed by winds. When winds were weak the microclimatic conditions resembled those of areas in the interior. Then drainage off the local hills and down the channel of the Colville River was often conspicuous, and sometimes amounted to moderate winds. The subnivean zones were considerably warmer than the colder zones, many areas having temperatures of 20°F or even higher on January 31, 1952, though a continuing prolonged cold period was affecting the region and air temperatures were then about -30°F.

IV. DISCUSSION

Importance to animals of the microclimatic conditions

Now that a variety of weather states, events, and sequences, a variety of microclimatic states, events, and sequences in several different microclimatic zones, and a number of other environmental factors have been briefly and roughly described, the question of the importance of each of these to the resident mammals and birds can be discussed. An understanding of the importance of each of these various conditions and factors, combined with the accumulated information of previous research and of the other observations and data of this research, provides partial answers to the basic question of how the resident mammals and birds manage to survive the severe arctic and subarctic winter conditions.

The several species of animals observed showed different types or amounts of activity during different periods of the day, during different types of weather states and microclimatic states, and during the different types of major events of the sequences of events (climates and microclimates) of the two winter periods investigated. They also showed considerable differences in type and amount of activity in the several major natural zones of the microclimatic fields of variables and distributions of materials.

Microclimatic Zones. The major microclimatic zones, in general vertically stratified, each graded into the next above and below, each was composed of several to many sub-zones, and each was considerably more distinct during some weather states, particularly states with rapid radiational cooling, than during others, such as late isothermal states of prolonged snowstorms. Associated with some of these major zones were relatively distinct groups of animals. The major zones were eight in number: Zone 1 consisted of the highest layers of air, such as those above the 60 to 100 foot levels. Conditions in it, usually relatively warm but often rather windy, chiefly affected high flying birds at the valley lowland areas, but affected other animals at higher areas, as at areas up on Birch Hill. Zone 2 consisted of the higher layers of the lower air, such as those about 20 to 60 feet above the surface. Conditions in it, usually less windy and appreciably cooler than conditions in Zone 1 but still relatively warm, chiefly affected the several species of birds and the tree climbers at the valley lowland areas, but also affected other animals at higher areas. Zone 3 consisted of the lower layers of the lower air, such as those about the 4 foot level of the standard weather shelters and some 2 or 3 feet below and 10 feet above it. Conditions in it, usually considerably colder than those of the zones above and with very little or no wind, chiefly affected birds, tree-climbers, large mammals, and man, but also at times affected many others. Zone 4 consisted of the lowest layers of air, such as those close to the snow surface to 1 or 2 feet above it, and for some purposes included the air lying at lower levels as in depressions and channels. Conditions in it, usually still colder and essentially windless, chiefly affected the birds and smaller mammals that moved about on the snow surface. Zone 5 consisted of the zones at and very close to the snow surface. Conditions in it, usually the coldest of all in midwinter and essentially windless, chiefly affected the birds and smaller mammals, especially the smallest ones, that ventured onto or moved about the snow surface. Zone 6 consisted of the layers within the snow-cover. Conditions in it varied considerably, but were usually relatively cold in the upper layers, and usually considerably warmer in the lower layers. They chiefly affected grouse-like birds and the small mammals of the zones above and below. Zone 7 consisted of the zones at and about the soil surface, including the air spaces at the base of the snow-cover, and including the upper layers of the soil. Conditions in it, usually much warmer in midwinter than conditions in any of the zones above, chiefly affected small mammals and their predators in the areas studied, but also affected others. Zone 8, consisted of the zones deeper in the ground (or in water). Conditions in it, usually the warmest zone in midwinter, chiefly affected the burrowers and hibernators (and aquatic or amphibious animals). The most important distinctions were between: 1) the higher layers of air, 2) the lower layers of air, 3) the zones at and close to the snow surface, and 4) the zones at and below the base of the snow-cover; and between the groups of animals associated with these zones: 1) the birds and hill mammals, 2) birds, tree-climbers, large mammals, and man, 3) surface feeding birds (including grouse-like birds, and small seed eating birds), hares, foxes, and other mammals of intermediate size, and 4) the subnivean small mammals (notably voles, squirrels, and shrews) and their predators (notably the weasels).

For the animal groups of the four biologically most important zones the sequences of the macroclimatic and microclimatic states and events (the macroclimate and the microclimates) of the different zones have quite different significances. The largest animals (such as moose, caribou, wolves, and foxes) are in general the best protected morphologically and physiologically from excessive energy losses (1, 35, 39, 40, 41), and are often active in the coldest zone. They are evidently not often seriously endangered by the hazards of the most severe conditions, including those of prolonged intense cold, strong cold winds, and deep soft snow-cover, but they tend to avoid such conditions. Although little information was gathered concerning this group it may be said that the animals of the group were notable for their ability to withstand, without apparent difficulty, the prolonged cold of the most severe cold period events of the continental interior. Their size, their very effective insulation (39, 40, 41), their adequate energy sources (food), and the calmness of the air during the coldest periods were among the most important adaptations and factors permitting them to be so successful and so independent of the environmental states and events.

The mammals of intermediate size (such as snowshoe hares and arctic foxes), that moved about on the snow surface, hence in the very coldest zones, also showed an activity remarkably independent of microclimatic states and events, so long as food was readily available. But at least some of these animals clearly sought out more favorable microclimatic conditions more frequently during the coldest microclimatic events than during the lesser cold periods and the warm periods. The factors permitting their success were largely the same as those listed for the large mammals. However adaptations of the feet and legs permitting them to travel on the soft snow surface and providing insulation against the extreme cold of the snow surface (commonly called "snowshoes") were also of great importance.

On the other hand the smallest mammals (such as red-backed mice, tundra voles, and shrews) were very much dependent on weather states and events (in this respect man resembled them, despite the great advantages of his technology). They had none of the benefits of size (such as the possible decreased rate of heat loss due to the decreased surface to mass ratio of large animals, and the importantly larger heat reservoir of large animals), and had very thin fur which provided very little insulation (22, 39, 41). During the coldest microclimatic events of the surface and atmospheric zones they confined their activities to the warm subnivean zone. There even during prolonged intense cold-snaps (see figs. 3, 4, 9, and 10), when even the subnivean zones became appreciably colder, these smallest mammals survived and even thrived, so long as food was readily available, and provided the snow-cover was sufficiently deep. During such cold events, and even during lesser cold periods (as those shown in figs. 19 and 21) they rarely came out into the cold surface zones. However during the winter warm periods (such as the snowstorms of figs. 6, 19, and 21, and the diurnal warm periods of figs. 7 and 19) when the surface zones were considerably warmer (with conditions similar to or warmer than those shown in curve 5, fig. 13; curve 4, fig. 15; curve 3, fig. 16; curves 1 and 5, fig. 20; and curve 1, fig. 22) or when surface conditions included temperatures at and above freezing (not shown but common in late winter), then the subnivean small mammals were considerably more active in the surface zones. During the many lesser cold periods, and the rather long total time during midwinter of generally intermediate conditions, they only occasionally ventured into the surface zones of the valley lowland areas. Even then, at least in some instances, they may have been escaping predators. When exposed for a matter of hours to conditions with temperatures below -20°F or even higher, they froze to death (as in non metallic live-traps or in cages with cotton for insulation). Some were found dead on the snow surface.

In sharp contrast the birds, large and small, showed an activity most remarkably independent of macro- and microclimatic states and events. Even the largest (such as the ravens, grouse, and owls) were, underneath their feathers, quite small animals, and the smallest (such as the chickadees and redpolls) were small indeed. Yet they moved through most of the zones of the greater temperature field regularly and with impunity. They were commonly in the higher warmer zones of the air, and roosted in these zones exposed in trees or further protected in still warmer microclimates, as in tree holes (though some of the grouse-like birds roosted in the warm zones of the snow-cover). They were also not infrequently in the coldest surface zones. The grouse-like birds (Tetraonidae) fed extensively in the cold surface zones, even during cold periods. Even the smallest fed in the coldest zones during the coldest microclimatic states. Furthermore while most of the animals had to endure only the coldest conditions without winds, these birds endured the same coldest conditions but with the equivalent "winds" of flight, and this was equally so for the smallest. Clearly, whatever other adaptations may have been important, the insulation provided by feathers must have been very effective and important. It is true however, that during the coldest events and in the coldest zones they did not fly much, but spent most of the daylight hours very actively feeding wherever food could be found. The smallest birds went into the coldest zones during the coldest states only because of the food that was there, a fact which emphasizes the importance of food. They also obtained grit and snow in the cold zones. Because most were active only during the daylight hours, and were inactive and losing energy during the long night, they had to replenish their energy stores especially vigorously and effectively during the short daylight period typical of the most severe midwinter cold-snaps. However so long as food was readily available they survived the worst natural conditions with little apparent difficulty.

Since the importance of the macro- and microclimatic states and events and of the other geophysical(and biological) factors varies not only with the group of animals associated with each of the four main microclimatic zones but also varies with the individual species, further details concerning the former type of variation may perhaps best be presented in terms of details of the latter type of variation. Because satisfactory observational data on animal activity under natural undisturbed conditions are hard to obtain and unavoidably incomplete, no full even qualitative description of the animal activity concurrent with the observed environmental conditions and its significance can be presented here. And no full interpretation of the accumulated observations can be given, nor can all the species of interest be given equally full consideration here. In these respects the biological information obtained during this research represents only a beginning, an early stage in the development of a vast and generally neglected field of research. Furthermore, because of the large number of observations obtained during this research, and time limitations, only a few highlights and general conclusions regarding the animals most intensively studied can be presented here.

Among the most interesting and intensively studied animals were the subnivean small mammals. Being very sensitive and in no way independent of microclimatic states, events, and zones, they most clearly showed the impact of the various events and the significance of the various zones. However since they spent most of the time hidden from view under the snow-cover they were in many respects the most difficult to study. They included:

1) The red-backed mice (Clethrionomys rutilis). These voles were found primarily at areas up on the valley lowland, rough-surfaced areas often with low vegetation but commonly including shrubby zones and trees. Most of the areas were relatively well drained. These animals were studied chiefly in the areas along the west bank of the Chena River west of the laboratory and in the adjoining area of low heath plants, scattered scrubby spruce trees, and tamaracks. The snow-cover there was deep and and soft, but was more exposed to and disturbed by the winds than the snow-cover of the lower areas. Though the surface zones were usually considerably warmer there than at the lower zones, the subnivean zones were appreciably colder (commonly 5 to 10°F colder). In midwinter these voles spent almost all of the time in the warm subnivean zones. They were quite common at some of the West Bank areas. They utilized the natural air spaces to a large extent, and usually reached the upper snow surface by using natural openings, as where small trees, branches, twigs, or other vegetation penetrated all or most of the snow-tunnels in, and to the surface of, the snow. The non-natural surface holes were apparently not often used and not often reopened when closed by light to moderate falls of snow.

Though very active under the snow-cover, they only occasionally ventured out onto the snow surface in midwinter, and rarely did so during the major cold periods. However, during the warm periods (such as those of figs. 6, 19, and 21) they were somewhat more active near or on the surface (as evidenced by more tracks and droppings). They were, in general, increasingly more active near and on the surface as the season progressed. Later in the season during the diurnal warm period peaks of generally warmer conditions (similar to but warmer than the diurnal warm periods shown for March in fig. 7, and for February in figs. 7 and 19), when many areas had surface zones with temperatures at and above freezing, these voles went into the surface zones and moved about on the snow surface considerably more. But most of the time they remained in the zones and in and under the snow-cover. While relatively tolerant of the cold, windless conditions to which they were occasionally and briefly exposed, they could not survive for even a matter of hours (as in non-metallic traps and cages provided with cotton for insulation) when exposed to conditions with temperatures below -20°F or even higher. When forced to the surface, as by predators, or when crossing narrow hard-packed sled, snowshoe, or ski trails, they could survive brief exposure to the cold surface conditions of cold periods (such as those of the medium curves of figs. 9 and 10). But they clearly depended on the warm subnivean microclimates for survival during these and the lesser cold periods of midwinter. While somewhat active in the zones within the snow-cover, detectibly so even during the lesser cold periods (such as those detailed in figs. 19 to 22), they were not conspicuously active at the snow surface until the seasonal warming (primarily due to increased solar radiation) caused conditions at areas of the surface zones to be even warmer than the conditions of the subnivean zones.

2) The tundra voles (Microtus oeconomus). These voles were found in low rank grassy and sedgy areas associated with the river channel (see fig. 2). These areas were evidently quite wet during the warm season, and may

have been flooded during periods of high water. Narrow zones of ice occurred at some of the lowest spots. Being low such areas tended to be cold pockets (in the surface and atmospheric zones) during the winter. The main areas where these animals were studied were the SD area (see figs. 1 and 2) and the wide grassy portion of the Bar Area. No other nearby areas were known to have significant populations of these voles (though some may have existed farther up and down the river). These two areas had the coldest cold zone conditions of all the areas studied. But they also each had a deep undisturbed snow-cover, and may have benefited from their low position and concave topography (see pages 98-99), hence they also had the warmest subnivean zones of all the areas studied. During the coldest period of the main 1952 cold-snap (see figs. 9, 11, and 12) temperature differences of from 90 to 100°F over a distance of about two feet, from the snow surface to the soil surface, were found at the SD Area. During colder cold-snaps (and in regions which normally have colder cold-snaps) even greater differences undoubtedly could be found. In the warmest subnivean zones of these areas, notably at the Bar Area, these voles were very active throughout the winter. They were not found at colder areas during the midwinter period. They constructed characteristic tunnels to the snow surface (see fig. 25), and commonly reopened the surface holes when they were closed by snowfall. But they very rarely came out of these surface holes, or out of other holes, to move over the snow surface. At the Bar Area, which had a population amounting to tens of animals, voles traveled over the surface only several times during the winter period studied (and most of these behaved as though they were in a hurry and seeking a way to get back below). Only once did one come out during a cold period (evidently an emergency). The surface holes were made throughout the winter, and were used repeatedly. But few were made during the dark, cold, shortest days, and these showed no evidence that the voles came near the surface often or remained there except very briefly. Many of these holes were closed or partially closed by frost, while considerably less, and much finer, frost formed on the rest of the area of snow surface. Other holes remained open. During the major midwinter warm periods they were appreciably more active near the surface, making new surface holes, reopening old ones, and leaving a few signs of having lingered at the surface openings. They appeared to be markedly more active in the zones near the snow surface during the later relatively warm stages of the period of rapid warming (of the zones of the snow surface, the upper layers of the snow-cover, and the lower layers of the atmosphere) that often followed the cold-snaps (see figs. 3, 9, and 10) than they were during the preceding extremely cold periods. But even then they showed only a slight amount of near-surface activity. The most striking instance of such an apparent relative burst of previously inhibited activity was the one that occurred during

FIGURE 25

the warming event of January 11, 1952 (fig. 9). Later as the season progressed, as the conditions in general became warmer and the diurnal warm period became longer and considerably warmer, the voles constructed more holes at a steadily increasing rate, and used them much more. Then they also used natural holes, especially those along willow shoots, those made by other animals, and those made by man (such as holes made by skis, ski-poles, snowshoes, mukluks, and by occasional missteps off the narrow packed-snow paths). By the end of February over 250 surface holes were kept open at the Bar Area (mostly at the wide, grassy, low area) where during the two earlier cold-snaps only about 20 existed (of which about one-third were closed by frost). Furthermore the voles also remained markedly and increasingly longer at the snow surface, leaving tracks and droppings at the widened surface openings. And they were active on the surface progressively farther from the surface holes, so that by late winter many of the openings had about them lightly packed, densely tracked and somewhat soiled areas, which extended a half-inch to an inch or more from the openings. By this time also the floors of their surface tunnels had become hard-packed and somewhat dirty. Repeated observations indicated that most of their near-surface activity occurred during the diurnal warm periods. Quite unlike the situation during the cold-snaps, when no important warm period events affected the surface zones for prolonged periods of time, during the later generally warmer periods (often characterized by clouds, short storms, and increasingly important events of diurnal warming) the animals could come to the surface frequently, easily avoiding the relatively short cold periods, to find quite warm surface conditions (see figs. 7, 19, and 21). During the periodic events (figs. 7 and 19) warm periods were available each day regularly, so that by a proper timing of their activities the voles could easily avoid the nocturnal cold periods and utilize the diurnal warm periods and the consequent local warm areas of the surface zone. Such regular events also provided helpful study situations with repeated and sharply contrasting conditions. The evidence clearly showed that these animals did avoid the surface zones during the cold period events but did go into them frequently during the daily much warmer periods. During the warmer conditions of late winter they clearly were also relatively active near and in the surface zones during the less warm, but sunlit hours of early and midmorning. In the late winter, while they appeared to be active near and at the surface at all hours, they were most active during the warmest hours, and then were most active at the warmest locally heated areas. Throughout the winter, however, they were active in the warm subnivean zones. There, when protected by an adequate snow-cover, and when adequate food supplies were available, they could thrive and even reproduce, quite unaffected by the cold events of the colder micro-climatic zones above. They were the most intolerant of cold of all the animals intensively studied, and were clearly dependent for survival on the continuously warm subnivean microclimates, microclimates which were critically important during the severe midwinter cold-snaps, but were also very important during the less severe cold periods of late winter and spring.

Another relatively intensively studied small mammal, both subnivean and arboreal, was:

3) The red squirrel (*Tamiasciurus hudsonicus*). These larger and more cold-tolerant small mammals lived in spruce groves, and were found wherever sufficiently large groves occurred. There they industriously gathered and stored spruce cones in the warm season, and industriously rediscovered them and fed on them during the winter. These groves were often rather small, and commonly consisted of only a few tens of trees. Squirrels were studied

at, and revealed quite different behavior at, two different types of areas: valley lowland areas, and higher areas on the crests and sides of hills. They were studied chiefly in the valley lowland areas of and west of the West Bank Area, and at the Birch Hill Squirrel Area. The lowland spruce trees were neither densely grouped nor very tall; the trees in the Birch Hill area were relatively tall and densely grouped. Under the trees the vegetation was sparse. Much litter from the trees covered the ground. Under the trees, and in the dense grove, the snow-cover was roughly half as deep as it was at the open areas. It was also more dense, and somewhat disturbed by snow that fell from the trees. The subnivean air spaces were well developed, but the subnivean microclimates were appreciably colder than those of the areas described above (averaging perhaps 5 to 15 or even 20^{o}F colder). All of the zones were much shaded, hence tended to remain somewhat colder in the daytime than they would have been otherwise.

At the hill areas red squirrels were relatively active throughout the winter, and often occurred in numbers. A group of about six was observed repeatedly at and near the Birch Hill station. There during the colder periods they made extensive use of tunnels in the snow and the spaces under the snow-cover and under logs and brush. Although the zone at the base of the snow-cover was colder than the corresponding zone at many lowland areas, the squirrels, in effect, compensated for this difference and gained warmth by utilizing burrows and warm insulated nests within the soil. One nest found at the base of a large spruce tree was about one foot in diameter and one foot below the level of the soil surface. During the colder periods of midwinter the squirrels traveled about in the cold surface zones very little, even though the conditions in these and the higher zones were commonly 15 to 20^{o} warmer than those in the corresponding zones of valley lowland areas. Though strongly reflecting the warmth of the higher layers of air over the valley lowland the zones in the air at the hillside areas also showed the effects of local surface cooling. Drainage of cold air through the area was commonly conspicuous, and at times amounted to light winds. Winds affected the hill areas considerably more than they did the lowland areas, but because of the protection offered by the spruce groves were usually light at the Birch Hill station.

During all events but the coldest the squirrels frequently climbed to branches about 3 to 10 feet above the surface, sometimes climbing higher, and there ate the seeds from spruce cones. From there they dropped cone scales and other debris at middens, some of which were quite large, and at other areas, thus indicating their activity. During the coldest periods of midwinter they were clearly less active and conspicuous above the snow-cover than they were during the midwinter warm periods and during the generally warmer conditions of late winter and spring. Since they returned to the subnivean zones at the end of each daylight period, they were not exposed to the usually cooler conditions of the surface and air zones at night. These conditions during cold periods were considerably warmer than the corresponding conditions at the valley lowland areas even during late winter. For example, during the successive cold night periods of figure 19 and the cold night period of figure 21, the minimum temperatures of the lower air layers (at a point 4 feet above the surface and representative of conditions several feet above and below) were respectively -12, -9.5, and -6, and -20°F (compare with dots for Ladd). Later in the season, especially during the diurnal warm periods, the squirrels became more aboreal, and considerably more active on the snow surface.

In contrast the somewhat fewer lowland squirrels showed very little activity above the snow-cover during the colder periods. Then little evidence of activity was observed, and squirrels were rarely heard calling or scolding. While open snow tunnels were present, they were few and had few tracks about them. But as the season progressed and conditions became generally warmer, the squirrels became increasingly more conspicuous and noisy, used more entrances and exits to the subnivean zones, and left many more tracks on the surface. Finally during the still warmer diurnal warm periods of late winter and spring, when local thawing was not uncommon, they made longer trips across the snow between trees and even made relatively long expeditions to the more distant isolated trees and groves. Being conspicuously well furred all over, including the ears and feet, these larger small mammals were clearly considerably less affected and less endangered by the cold periods of midwinter than were the voles. But they clearly avoided the cold microclimatic zones during the coldest microclimatic events, and then restricted most of their activities to the warm subnivean and subterranean zones. Those living in the considerably warmer hill areas behaved similarly, but were conspicuously more active above the surface in midwinter, and were not affected by the extreme conditions of the cold-snaps, conditions which profoundly affected the lives of the lowland animals. Provided with protecting microclimatic warm zones and adequate food supplies the red squirrels managed to survive the most severe winter conditions with little apparent difficulty.

Of the small predators, the shrews were entirely subnivean, while the weasels were active in the surface zones as well as in the subnivean zones.

4) The weasels (*Mustela erminea* and probably also *M. rixosa*) occurred at many areas of the valley lowland and lower areas, and of the nearby hills.

Most of the evidence of their activity was found in areas known to have populations of voles, notably the Bar Area, the tongue of lowland south of the river, the West Bank areas, and areas along the Chena Trail. They were clearly more cold-tolerant than the voles, occasionally coming out into the snow surface zones to make relatively long trips and explorations (often hundreds of feet long) on the snow surface. Most of these excursions were made during winter warm periods, particularly during the relatively warm snowstorms, and especially during warm nights. They were occasionally active on the snow surface during colder periods, but were clearly least active in the surface zones during the coldest periods. They became increasingly more active in the surface zones as the season progressed and conditions became generally warmer. But this increase was small compared to that shown by the red squirrels. They were not clearly much more active during the diurnal warm periods than during the cooler parts of the day, but did seem to be less active in the surface zones at night. They were more active at the warmer hill areas, but were about as active at the valley lowland areas as at the colder lower areas of the river and elsewhere. They were, however, not very active in the surface zones at any time. In most of the areas studied they made surface trips at most only several times during the winter period studied, and usually made them only once. Most of these areas were on the valley lowlands. They were clearly somewhat more active than this at some areas up on Birch Hill and at other hilly areas. Thus most of the time they were in the subnivean zones, where they explored and hunted actively and where they had burrows and nests. Because of this behavior they were usually not exposed to the conditions of the colder zones near the surface and above nor were they often directly exposed to the winter cold period events. When they did come to the surface they usually used natural holes, but occasionally they made their own (which they apparently usually used only once). Their surface trips appeared usually to be meandering explorations, as along the upper edge of the river bank (which had many natural holes), or at Chena Trail areas (which had many shrubs, and trees, and thus many natural holes). Once one emerged from a hole at the lower edge of the sunlit east bank (west of the laboratory) and partly dragged and partly carried a vole over the snow surface of the river down a distance of several hundred yards to another hole. Though more cold-tolerant than the smaller species, they usually were not exposed to the cold conditions of the colder zones during the winter (evidently being exposed even less than the red squirrels), and usually benefited by, and at times (as when resting) depended upon the warm subnivean microclimates. Provided with the protection of the warm microclimatic zones, and an adequate supply of prey species, they survived the most severe winter states and events with little apparent difficulty.

5) The shrews (Sorex cinereus and possibly others), in contrast, were not tolerant of cold, and rarely came out into the cold surface zones (where they were occasionally found dead), but instead hunted actively throughout the winter in the warm subnivean microclimatic zones. They occurred at the Bar Area and at other relatively warm areas where the voles were also numerous. They appeared to be somewhat more active in the surface zones (evidently during the warmer periods) of the higher hill areas and zones of thawing (as about the bases of trees and stumps and about logs) these animals left the truly subnivean zones somewhat more. Then they explored about the bases of natural openings through the snow (then often quite wide because of thawing) including those of the locally warm zones about trees, branches, and logs. Although when provided with the protection of the

warmest microclimates and adequate food supplies these animals did manage to survive the winter fairly well, some mortality was observed.

Of the mammals of the colder surface zones only the snowshoe hares were intensively studied.

6) Snowshoe hares (Lepus americanus) were common at this time at many valley lowland and hill areas of the Fairbanks region. They were found wherever extensive areas of brush or low growth occurred, especially along the rivers in areas with dense thickets of young willows. They were studied mainly at the Bar Area and at adjoining areas of valley lowland north of the river. In the Bar Area they fed extensively on willow shoots throughout the winter, traveling over the cold snow surfaces and in the cold surface zones apparently more concerned with food than with the low temperatures of this low area. However they moved about the snow surface and fed conspicuously more actively during the midwinter warm periods than during the cold-snaps and other cold periods. They made and used tunnels or burrows into the snow commonly only during the prolonged cold-snaps (see fig. 26). Though well used during the cold-snaps, most of these were abandoned soon afterward when warmer conditions returned. Snow shelters and burrows which were used during later lesser cold periods were also found but were uncommon. The hares became increasingly active later in the season as conditions became generally warmer, and left increasingly large numbers of tracks and runways then. But they appeared to be more active during the twilight and daylight hours of early and midmorning, and also of the afternoon and evening, than during the warmest hours of the diurnal warm periods. They were relatively active during the warm periods of storms, and appeared to be relatively inactive at night especially during the colder periods. They appeared to be appreciably more active in general at the hill areas than at the lowland areas, but no-

where were observed to be more active than at the feeding areas of the Bar Area. They were very well furred, especially on the legs and feet. While their wide furry "snowshoes" helped them to travel over the deep soft snow-cover (see fig. 28), they also provided very effective insulation against the cold surface. The slight depressions of their foot prints brought them into contact, in effect, with the somewhat warmer deeper layers of snow. Their mode of locomotion, often employing long hops, effectively permitted them to go unhindered up and over stretches of snow, instead of struggling through it, and also permitted them to contact the cold surface considerably less. Although these animals have developed adaptations allowing a high degree of tolerance of the commonly very low temperatures of the snow surface and surface zones of air and snow of low areas, even they apparently utilize the protection of the warmer microclimatic zones, especially during cold-snaps. Provided with adequate supplies of food, as by the willow

FIGURE 26

thickets of the Bar Area, they managed to survive the most severe winter conditions with little apparent difficulty.

Of the other larger animals: Foxes were active in the study areas during most types of environmental events. Not enough observations were made to even roughly determine their activity patterns. They appeared to be more active later in season. Their dens, in the warmer zones of the soil, were not found. Dogs survived the coldest periods easily, but were well fed, were not usually in the coldest zones, and when resting curled up tightly to keep warm. Bears had dens, in the warmer zones of the soil, in the Big Delta area, and though a search was made for one reported den there it was not found. Human beings avoided the conditions of the cold-snaps whenever possible, usually by retreating to the warm climate of their buildings. It was difficult and at times hazardous for them to try to move through the deep, soft, snow-cover without snowshoes or skis. Even with these aids travel over unpacked snow-cover was difficult. Well fed and clothed they could work, even inactively, in the coldest zones during the coldest microclimatic events, but usually with considerable discomfort. Some used the subnivean warm zones to delay the freezing of water, but most were unaware of the structure of the temperature fields, and had not learned to benefit from the warm zones, or from the insulation which made the warm zones possible.

Birds

Some birds were present during the winter in all of the regions investigated. While a variety of birds were observed at areas in the continental interior, few were observed at areas on the Arctic Slope and Arctic Coast. A few species were studied repeatedly, but most were observed only infrequently, often only once or at most a few times, during the two winter periods studied. The species most intensively investigated were:

1) The redpolls (Acanthis hornemanni and A. flammea). These small birds were quite common at areas of the valley lowland and of the adjoining hills wherever suitable food materials could be found. They appeared to feed primarily upon the seeds of birch catkins and alder cones, but also fed upon other kinds of seeds and upon buds. They were active only during the daylight period each day, a relatively short period of time during mid-winter, but one which rapidly lengthened as the season progressed. Then they flew about in the temperature fields of the air, from the higher warmer zones, through the colder lower layers of air, even to the coldest surface zones. Typically during most of the daylight period they were active in the lower layers of air, usually several feet above the surface in shrubs and small trees (mainly alders and birches - see fig. 1). As they fed upon the seeds of these plants they dropped scales, seeds, catkins, and cones on the snow surface below, often darkening the surface with such debris (see figs. 27 and 28). At times they flew to the snow surface to collect the fallen seeds. Quite unlike the smallest mammals, which clearly depended upon the warm, favorable, subnivean microclimates for survival and rarely went out into the surface zones during the cold periods, these small birds regularly went into the coldest zones and survived contact with the most extreme cold conditions to be found during cold-snaps. Regardless of the surface temperatures, they would fly to the surface to pick up the seeds they had just scattered there. Figure 27 shows tracks made on the surface of the snow at the station SD when surface temperatures were -60 to -70°F during the mid-morning hours of January 10 (see figs. 9, 11, and 12). During such cold conditions they retracted their legs and rolled about on

FIGURE 27

FIGURE 28

their bellies propped by wings and tail (note wing marks on the snow surface in fig. 27). At such times they fell from one side to the other, and sometimes fell forward, as they moved about in attempts to reach the few scattered seeds. In contrast, during the warmer periods they hopped about upright with their legs fully extended in the usual manner (note tracks in the background in fig. 28). Figure 28 also shows alder cones, scales, and seeds scattered about on the surface under the shrubs by the redpolls. These birds will also enter the snow-cover, by way cf natural holes, to feed upon seeds within and under the snow-cover (11). Evidently these birds went wherever they could find food, and were in general more concerned with finding enough food than with avoiding the coldest microclimatic zones. Provided with adequate supplies of food they appeared to survive all types of microclimatic states and events in all of the main microclimatic zones, and to survive them with little evident difficulty.

2) The black-capped chickadee (Parus atricapillus). These small birds were quite common at certain local areas of the valley lowland, as near the laboratory and near a garbage dump. They fed upon dog-food and refuse at the laboratory and dump areas, pecked about the bark of trunks, branches, and twigs of poplars and other trees and shrubs, and collected seeds and buds from trees and shrubs. They were active only during early dusk. They made numerous brief flights from twig to twig and from bush to bush in the lower layers of air, and occasionally made longer flights. They obtained snow from trees, shrubs, and tops of buildings, but occasionally went to the surface zones for snow and for grit. They usually remained in the surface zones only briefly, especially during cold periods, but sometimes remained longer when actively feeding on refuse there. During a cold period (about 1450 January 19) temperatures of -42 to -48°F were

measured at the generally snowless ground surface where they were feeding at the dump. There they also lingered on much warmer areas of cooling but still warm garbage. During cold-snaps they flew very little, were very quiet and inconspicuous, and kept their feathers greatly fluffed out. They also rolled about on the surface, legs retracted, as little fluff-balls, when the surface was extremely cold. During lesser cold periods they were considerably more active and conspicuous, but commonly remained at the higher levels (such as the 40 to 80 foot levels) of the lower layers of air. They were much more active in all zones during the warmer conditions of late winter. Two were observed to roost at night in tree-holes about 20 feet up in the poplars near the laboratory. Conditions at that height were commonly 5 to 15°F warmer than those of the surface zones of the same area; and conditions in the small, dry, deadwood-walled chambers of the tree-holes, when warmed by the presence of the birds, were commonly 5 to 15°F warmer than air outside. The differences were greatest during cold periods. Thus the conditions to which these birds were exposed during the long midwinter nights were markedly warmer than those of the lower air layers, as measured at standard weather shelters, and were much warmer than those of the lower still colder zones. No mortality was observed, though Bent (5) reports black-caps found dead in the woods during cold-snaps. Provided with adequate supplies of food and protected roosts these birds survived the most severe conditions with little apparent difficulty.

3) The Hudsonian chickadee (Parus hudsonicus). These birds were not common, but were observed several times feeding high in spruce trees up on Birch Hill. During the winter of 1951-52 the spruce trees had an unusually heavy crop of cones, thus they provided abundant food for these birds (and also for redpolls, pine grosbeaks, white-winged crossbills, and

for other homoiotherms). Though these chickadees were observed feeding in the relatively warm zones of air up on Birch Hill during the cold-snap of January 17-21, 1952, none were observed in the spruces of the lowland areas at that time. Others were observed at other hill areas, and later one was heard at a lowland area. No mortality was observed. Bent (5) reports a suggestion that this species may be hardier than the previous species since no birds of this species were found dead during cold-snaps when black-capped chickadees were found dead. An alternate possibility is that the black-capped chickadees were exposed to more severe conditions. Not only do they feed at the colder lowland areas, but also they commonly feed in the lower parts of trees and shrubs (while the Hudsonian chickadees characteristically feed in the highest parts of the spruces).

4) The pine grosbeak (Pinicola enucleator). These somewhat larger small birds were relatively common during the winter of 1951-52, possibly because of the large spruce-cone crop. At lowland areas they were usually seen feeding actively in the tops of spruce trees, sometimes calling loudly, or flying at a height of several tens of feet for distances of hundreds even thousands of feet between groves of trees. They appeared to be active during all weather states, but were clearly more conspicuously active and noisy during the warmer conditions of late winter. One flew over the station SD, about 40 feet up, through air with temperatures of -50 to -52°F, at 1350 January 10 (see fig. 9). They were usually active in the upper levels of the lower layers of air, but also commonly went into zones both higher and lower. They were also active up at hill areas, and during late winter fed on fallen seeds on the snow surface at areas up in the hills. Provided with adequate supplies of food they appeared to survive the most severe winter conditions with little difficulty.

5) The northern raven (Corvus corax). These large birds were common at areas near human settlements, where they fed primarily on refuse. They were common near the laboratory area and the dump area. They were usually seen flying by at heights of about 40 to 80 feet, perching in the tops of the tallest trees, or feeding in the surface zones. They were observed to fly in layers of air with temperatures of -50 to -52°F (1230 January 10) and to land at the surface during cold-snaps, where temperatures were measured to be -55 to -58°F (1445 January 10) on snow, and about -42 to -48°F (1430 January 19) on soil and debris at the dump (where 25 to 30 birds were gathered). They were appreciably more conspicuous and noisy away from feeding areas during late winter and not infrequently chased one another in skillful flight then. They were present at both lowland areas and hill areas. They were occasionally observed to fly above the 150 foot level in the air. Several sat in the tree tops in the warmer zones of air at the top of Birch Hill (where temperatures were -20 to -22°F at 1330) during the cold day of January 20 (when temperatures were -60 to -64°F in the surface zones of the low areas, about -50 to -52°F in the lower layers of air at valley lowland areas, and about -45 to -48°F at the 40 foot level at 1330; see fig. 10). They appeared to go wherever food could be found regardless of the winter conditions, and provided with adequate supplies of food survived the worst conditions with little apparent difficulty.

6) The grouse and grouse-like birds (the Alaska sharp-tailed grouse (Pedioecetes phasianellus), the Alaska spruce grouse (Canachites canadensis), the Yukon ruffed grouse (Bonasa umbellus), and the Alaska ptarmigan (Lagopus lagopus)). These birds all occurred in the Fairbanks area. The sharp-tailed grouse were relatively common at local areas of the valley lowland. They fed on the snow surface, extensively walking about from

plant to plant and eating buds and slender twigs. They were not observed during cold-snaps, but their tracks indicated that they fed on the snow surface then too. They roosted in chambers without openings in the snow-cover. Thus not only did they benefit from the naturally warmer conditions of the mid-layers of the snow-cover, but also they benefited from the additional warmth which developed when the enclosed well-insulated spaces were further heated by their own bodies. They also fed on buds and twigs up in shrubs and small trees and flew for short distances in the lower layers of air. During late winter they were more conspicuous in the lower layers of air, and were also appreciably more active in the surface zones, possibly partly because food was harder to find in the surface zones then.

The spruce grouse were observed only at areas up on Birch Hill. There they were seen feeding in groups of 2 or 3 up in shrubby birches as they fed near the Birch Hill Squirrel Area. They moved about from twig to twig at heights of 10 to 20 feet, audibly pecking and flapping their wings for balance, and occasionally flew to nearby trees and shrubs. Once they were observed to continue feeding through late twilight. Tracks in the area were presumably made by these birds, but they were never observed in the surface zones.

Ruffed grouse were not seen, but were reported at areas in the hills. Some of the tracks observed on the snow surface at hill areas, especially on sunny south-facing slopes during late winter, were almost certainly made by this species. The grouse tracks and trails observed at areas on Birch Hill were made either by this species or by the preceding species.

Willow Ptarmigan were observed once in the interior, at dusk (1430 January 30) at the Bar Area during a midwinter warm period (a snowstorm with cloudy skies and temperatures of 10 to 15°F). They were walking about on the soft new snow (sinking in 2 or 3 inches despite their "snowshoes"), feeding on weeds and twigs, and occasionally flying. They finally flew off into the darkness.

Other birds were also seen occasionally. Alaska Jays (Perisoreus canadensis) were seen in the lower air layers (1 to 40 feet above the surface), gliding about, watching, and calling at the poplar grove of the BL station, during the initial cooling stage of the cold-snap of January 17 to 21, 1952. Temperatures then (0920 January 17) at the 40 foot level were about -10°F, while temperatures at the 1 foot level were from -20 to -30°F (variable because of winds). Later in the season they were seen or heard at spruce groves across the river, at the base of Birch Hill, at the Birch Hill Squirrel Area, and at other places, but at none of these times were the temperatures below -10°F. Hairy woodpeckers (Dryobates villosus) came to the poplars of the BL area twice. There they hunted about the upper parts of tall poplars, evidently feeding. At the first time (1245 January 4) conditions included a low overcast, light snowfall, calm, and temperatures about 7 to 8°F in the lower layers of air. At the second (1300 January 24) conditions included some high clouds, calm, and temperatures at the 40 foot level of about -25°F. Then the woodpecker was feeding actively in poplars at a height of 40 to 60 feet, occasionally calling. At another time (1600 February 25) when skies were partly cloudy and temperatures were 10°F, one was observed at the Birch Hill Squirrel Area. Thus contrary to local opinion these birds were present in the Fairbanks area throughout the winter.

A white-winged crossbill (Loxia leucoptera) was observed feeding on the cones at the top of a tall spruce tree of the Birch Hill Squirrel Area. Then (1520 March 5) temperatures at the Birch Hill area were about 1°F.

Shortly before skies had cleared, temperatures had started to fall, and a late winter cold period had begun to develop (see fig. 21).

At least two species of owls were present in the area. A northwestern horned owl (Bubo virginianus) was caught nearby. An owl, almost certainly a Richardson's owl (Cryptoglaux funerea), hunted in the Birch Hill Squirrel Area, and later, at night, was heard calling high up in a birch and spruce grove a short distance away. Then (1950 March 12) the night was essentially clear, but was warm (20 to 25°F at the Birch Hill Station) and somewhat windy (10 m.p.h. at Ladd). Other owls of this species were captured and brought to the laboratory.

Mammals and Birds of the Arctic Slope and Arctic Coast

Two other species of considerable interest were the lemmings (Lemmus trimucronatus and Dicrostonyx groenlandicus). These mammals lived, sometimes in large numbers, on the Arctic Slope of Alaska, and at comparable areas of northern Canada and elsewhere. At Point Barrow, and to a lesser extent at Barter Island, an attempt was made to determine the types of microclimatic conditions available to these lemmings, the types to which they were exposed, and the use by the lemmings of favorable types, if any. As indicated above, the geophysical conditions of this region were quite different from those of the continental interior, and were in general appreciably more severe. Although the coldest zones did not usually become so extremely cold, they were subject to persistent winds, and tended to remain cold longer. The zones in and under the snow-cover and in the upper layers of the ground were all appreciably colder, and also remained cold longer. Yet the lemmings were abundant at times. Very important among the conditions making possible this success were the favorable warm microclimates which developed under areas of relatively deep semi-permanent snow-cover. Such warm zones were particularly well developed under the deeper snow of small local areas of rough topography, including a) areas of high-center polygonal ground, b) the more deeply cut drainage systems, c) bluffs, d) banks at the margins of lagoons, ponds, and other bodies of water, and e) other areas where non-migratory drifts provided thick insulation throughout the winter. Such warm zones were not found at the relatively wide, flat expanses of low-center polygonal ground, or at other flat areas of the tundra, although even at such areas the snow-cover provided some protective insulation. Lemmings were not found at any of these flat areas, though several were carefully searched. They were certainly not common at such areas, if present at all. On the other hand they were common (during the winter of 1951 to 1952) in the warm microclimatic zones of the areas of rough topography, especially those of high-center polygonal ground. There in the naturally developed air spaces beneath the snow, or in tunnel networks through the loose, open, depth-hoar and not uncommonly through more dense but still granular snow, lemmings were very active and fed extensively on the exposed subnivean vegetation. Evidence of lemming activity in the form of connecting tunnels, and scattered feeding areas, was also easily found at the other areas with deep semi-permanent drifts of snow. Extensive feeding areas were commonly under 14 to 30 inches of snow, in air spaces with temperatures commonly 0 to 15°F, and usually above 5°F, even shortly after a prolonged cold-snap, (during the period of study from January 26 to February 4, 1952). Connecting tunnels were usually under at least one foot of snow, were often under still deeper snow, and were occasionally under snow only several inches in depth (see figs. 29 and 30.) Figure 29 shows the hard packed tundra snow, winds, the thermistor thermometer, and a connecting tunnel running under one foot of snow along the

FIGURE 29

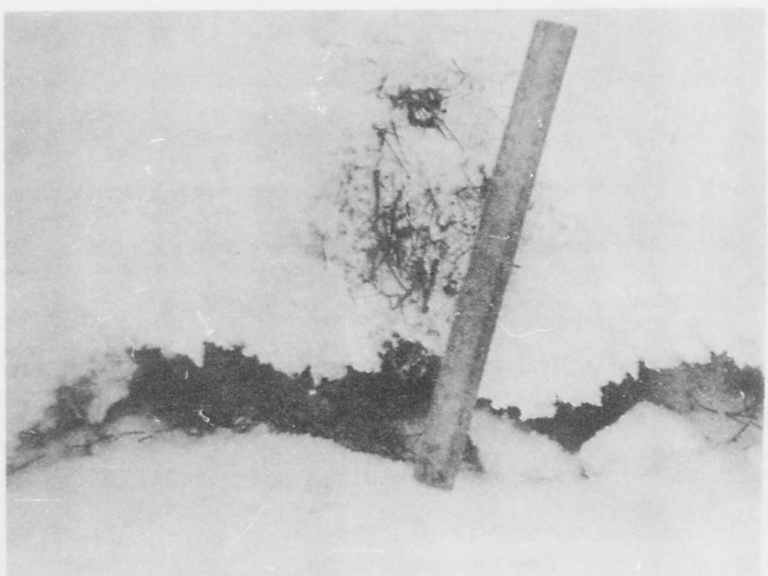


FIGURE 30

bank of a pond. Figure 30, depicting the same tunnel in more detail, shows the size of the tunnel, some depth-hoar crystals on the roof of the tunnel (indistinct), and vegetation and droppings left by lemmings which fed as they traveled along the tunnel. Temperatures in such tunnels varied more widely than those of the subnivean feeding areas, and in late January after a prolonged cold period were found to vary from -10 to 16°F.

The two species of lemmings may differ in their toleration of cold. Lemmings of the genus Dicrostonyx appear to be the more hardy of the two, digging (often through quite dense snow) and using colder tunnels, even occasionally coming out onto the snow surface (30, 46). Apparently lemmings of the genus Lemmus also used these tunnels, but typically utilize the subnivean warm zones, and go out into the cold surface zones only exceptionally (where they are sometimes found dead) (30, 36). Later in the season, when conditions become generally warmer, different patterns of behavior undoubtedly occur.

The lemmings, famous for their pronounced population fluctuations or "cycles" with peaks recurring on the average every 3 to 4 years, were increasing in numbers at the time of these studies. The Point Barrow populations had had peaks during the springs of 1946 and 1949, and had been very low in numbers during 1950 and 1951, showing a slight increase during 1951. During these studies, in early 1952, they appeared to be relatively common, at least locally in the warmer subnivean zones. Their activity, apparent response to microclimatic conditions, and other patterns of behavior may well differ during years of low and years of high numbers. The importance of the snow-cover in the lives of these animals is emphasized by the facts 1) that even during a year of a population peak (1946) little evidence of their activity was observed in the snow surface zones, and 2) that the abrupt decline in numbers of the years 1946 and 1949 occurred at the time the snow-cover thawed and vanished (36).

Evidence of activity of several other animals was observed at areas on the Arctic Coast of Alaska. These animals were: 1) the arctic fox (Alopex lagopus), which left tracks and trails in fresh snow along a ridge where it was evidently hunting lemmings. These animals frequented the surface zones, apparently even during cold periods. They were very well furred, and therefore quite cold tolerant (39, 40, 41). Provided with adequate food they appeared to survive the most severe arctic conditions with little difficulty. 2) The weasels (Mustela sp.: M. rixosa or M. erminea or both) also left tracks in the new snow, as they explored and traveled across the tundra, presumably hunting for areas with lemmings. These small mammals were largely subnivean, and provided with the protection of warm microclimatic zones and adequate supplies of prey species survived the arctic winter conditions with little apparent difficulty. 3) A bird, a "sea pigeon", almost certainly a Mandt's Guillemot (Cepphus grylla) was observed in the lower layers of air at the Point Barrow camp, when temperatures there were 0 to 10°F. It fed at the open water of the Arctic Ocean, which was unusually close to shore at that time (being less than 1/2 mile offshore). These birds are reported to take refuge in crevices of the pack ice and in (warm) air pockets in and under the sea ice (4).

At Umiat several other types of animals were observed. Wolves (Canis lupus) were numerous near the camp and at the dump area. They were very well furred and highly cold tolerant (39, 40, 41). Hence they could and did remain in the area throughout the winter, scavenging at the dump and surviving with little difficulty. Moose (Alces americana) walked through the snow-cover (which was commonly about 2 feet deep), lay down in the snow, and foraged at areas in and along the Colville River. They were also present all winter. Very little evidence of small mammals was observed, though a few areas with recently used subnivean spaces and tunnels and a few surface holes and tracks were found. Ravens (Corvus corax) fed in numbers throughout the winter at the dump. Provided with this source of food they survived the long, dark, and cold winter conditions with little apparent difficulty. Willow ptarmigan (Lagopus lagopus) were present in numbers at areas in and near the Colville River. There they walked about on the snow-surface extensively, fed on buds and twigs, and roosted in chambers made in the snow. Used roosting chambers were very common at the main feeding areas at an island in the river channel. There the snow was 20 to 28 inches deep, and temperatures at the base of the snow-cover were generally 10 to 23°F (on January 31, 1952). The birds flew through the lower layers of air and perched in low willows, when the temperatures there were about -20°F to -25°F (during midday January 31). Later (1020 February 1) a gyrfalcon (Falco rusticolus) was observed watching one of these ptarmigan feeding areas from a perch about 10 feet up in the willows. After a short period of time it flew away down the river, flying at a low level. Temperatures in the lower air layers then were about -23°F. Conditions then also included an overcast, light snowfall, and light to moderate winds.

V. SUMMARY

1) Winter microclimatic conditions at areas in the continental interior of Alaska, ~~particularly near Fairbanks, Alaska,~~ and at areas on

the Arctic Slope of Alaska were measured and observed during the 1950-1951 and 1951-1952 winter periods.

2) The microclimatic and macroclimatic conditions, consisting of changing fields and distributions of quantities, were approximately determined in the continental interior for a variety of habitat types at areas of valley lowland, adjoining hills, small depressions, and the Chena River channel. The determination of temperature fields was emphasized.

3) The microclimatic and macroclimatic conditions were approximately determined for a variety of microclimatic and macroclimatic states and events in the several main microclimatic zones. The environmental events primarily studied were: a) cold-snaps, b) midwinter warm periods (storms), c) periods of rapid warming, d) periods of rapid cooling, e) periods of regular diurnal variation, and f) late winter cold periods. The main microclimatic zones were: a) the upper layers of the lower atmosphere, b) the lower layers of air, c) the upper surface of the snow-cover and the layers of air and snow respectively just above and below it, and d) the ground surface and the layers of air (and snow) and soil respectively just above and below it.

4) Concurrent with the determinations of conditions of the physical environment, observations were made concerning animal activity and the biotic environment. The animals chiefly studied were the small mammals: *Clethrionomys rutilus*, *Microtus oeconomus*, *Tamiasciurus hudsonicus*, *Mustela erminea*, *Sorex cinereus*, and *Lepus americanus*; and the birds: *Acanthis sp.*, *Parus atricapillus*, *Corvus corax*, and *Pedioecetes phasianellus*. These animals, and others, comprised groups corresponding to the four main microclimatic zones.

5) An attempt was made to determine the response of these animals to conditions in the several zones during the principal microclimatic states and events. In general, the animals of all zones avoided the most severe conditions of the coldest zones, (the snow surface zones) during the coldest events (cold-snaps) by retreating to warmer, more favorable zones (such as the subnivean zones). The animals tended to be considerably more active in the snow surface zones at the generally warmer areas up on hills than at the colder lowland areas. They were also considerably more active in the surface zones during the generally warmer conditions of late winter.

6) The subnivean small mammals were dependent for survival upon the continuous existence of the warm subnivean microclimates. Temperatures in the warmest subnivean zones were commonly 20 to 25°F even during cold-snaps. Temperature differences across a snow-cover two feet in depth were observed to be as much as 90 to 100°F in a small depression "cold pocket" during an intense cold-snap. During warmer periods subnivean temperatures were commonly 25 to 30°F.

7) The small birds at times fed on seeds on the cold snow surface when it had temperatures of -60° to -70°F. During such conditions they exhibited special (adaptive) behavior.

8) Relatively warm and cold microclimatic zones were also found at areas on the Arctic Slope and on the Arctic Coast. There the environmental conditions were quite different from those of the continental interior of Alaska. There too small mammals utilized the protection of the warmer microclimates of certain subnivean zones.

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REFERENCES

1. Allee, W. C., A. E. Emerson, O. Park, T. Park, and K. P. Schmidt. Principles of animal ecology. Philadelphia; Saunders, 1949.

2. Anthony, H. E. Field Book of North American Mammals. New York; G. P. Putnam's Sons, 1928.

3. Archiv fur Meteorologie, Geophysik und Bioclimatologie; Ser. A Meteorology and geophysics; Ser. B Biological climatology. Vienna; Springer-Verlag.

4. Bailey, A. M. Birds of Arctic Alaska. Pop. Ser. No. 8. Denver; The Colorado Museum of Natural History, 1948.

5. Bent, A. C. "Life histories of the North American jays, crows, and titmice." Washington, D. C.; Smithsonian Institution, 1946.

6. Black, R. F. "Terrain and permafrost in the Barrow area, northern Alaska." U. S. Geol. Survey Permafrost Program Progress Rept. 9, 1947.

7. Black, R. F., and W. L. Barksdale. "Terrain and permafrost in the Umiat area, Alaska." U. S. Geol. Survey Permafrost Program Progress Rept. 5, 1948.

8. Black, R. F. and W. L. Barksdale. "Oriented lakes of northern Alaska." Journal of Geol. 57: 105-118, 1949.

9. Burt, W. H., and R. P. Grossenheider. A Field Guide to the Mammals. Boston, Mass.; Houghton Mifflin Co., 1947.

10. Cabot, E. C. "The northern Alaskan Coastal Plain interpreted from aerial photographs." Geog. Rev. 37; 639-648, 1947.

11. Cade, T. J. "Sub-nival feeding of the redpoll in interior Alaska: a possible adaptation to the northern winter." Condor, 55; 43-44, 1953.

12. Church, J. E. "Snow and snow surveying." In: Meinzer, O. E. (ed.). Physics of the Earth-hydrology. 9; 83-149. New York; McGraw-Hill, 1942.

13. Corps of Engineers, U. S. Army. "Interim report to Snow, Ice, and Permafrost Res. Estab. (SIPRE)." Univ. of Minn., Eng. Expt. Sta., 1950.

14. Crawford, C. B. "Soil temperatures (a review of published records)." Nat. Res. Council of Canada, Div. of Building Research, Ottawa, 1951.

15. Dice, L. R. "Notes on the mammals of interior Alaska." Jour. of Mammalogy. 2; 20-28, 1921.

16. Dorsey, N. E. Properties of Ordinary Water-substance. New York; Reinhold Pub. Corp, 1940.

17. Formozov, A. N. "Materials to the knowledge of flora and fauna of the USSR." Published by the Moscow Society for the Investigation of Nature, New Series, Zoological Department, Issue 5. Moscow, 1946.

18. Geiger, R. The Climate near the Ground. Cambridge, Mass.; Harvard Univ. Press, 1950.

19. Gerdel, R. W. "Penetration of radiation into the snow pack." Trans. Am. Geophys. Union. 29; 366-374, 1948.

20. Griffin, D. R., H. T. Hammel, H. M. Johnson, and K. S. Rawson. "The comparative physiology of thermal insulation" - a final report under Contract AF 33(038)-12764 between the Arctic Aeromedical Laboratory and Cornell University, 1953.

21. Hamilton, W. J. American Mammals: Their Lives, Habits, and Economic Relations. New York; McGraw-Hill, 1939.

22. Hammel, H. T. "A study of the role of fur in the physiology of heat regulation in mammals." (Thesis). Ithaca, New York; Cornell Univ., 1953.

23. Haviland, M. D. Forest, Steppe and Tundra. Cambridge; Cambridge Univ. Press, 1926.

24. Jenness, J. L. "Permafrost in Canada: origin and distribution of permanently frozen ground with special reference to Canada." Arctic. 2; 13-27, 1949.

25. Johnson, H. M. "Preliminary ecological studies of microclimates inhabited by the smaller arctic and subarctic mammals." Science in Alaska. Proceedings, Second Alaska Science Conference, Alaska Div. AAAS. 125-131. 1951.

26. Klein, G. J. "Canadian survey of physical characteristics of snow-covers. Tech. Mem. No. 15. Nat. Res. Council Canada, Associate Committee on Soil and Snow Mechanics, Ottawa, 1950.

27. Klein, G. J., D. C. Pearce, and L. W. Gold. "Method of measuring the significant characteristics of a snow-cover." Tech. Mem. No. 18 Nat. Res. Council of Canada, Associate Committee on Soil and Snow Mechanics, Ottawa, 1950.

28. Manniche, A. L. V. "The terrestrial mammals and birds of northern Greenland." Meddelelser om Gronland. 45; 1-20, 1910.

29. Morgan, A. H. Field Book of Animals in Winter. New York; G. P. Putman's Sons, 1939.

30. Morrison, P. R., F. A. Ryser, W. J. Tietz. "Studies on winter adapted small mammals," a research report under Contract No. AF 33(038)-11860 between the Arctic Aeromedical Laboratory and the University of Wisconsin. 1953.

31. Muller, S. W. Permafrost or Permanently Frozen Ground and Related Engineering Problems. Ann Arbor, Mich.; J. W. Edwards, Inc., 1947.

32. Nakaya, Ukitiro, and others. "Investigations on snow." Hokkaido Imperial University, Sapporo, Japan. (a series of papers). 1934.

33. Newburgh, L. H., (ed.) Physiology of Heat Regulation and the Science of Clothing. Philadelphia; Saunders, 1949.

34. Nikiforoff, C. "The perpetually frozen subsoil of Siberia." Soil Science, 26; 61-81, 1928.

35. Prosser, C. L., (ed.). Comparative Animal Physiology. Philadelphia; Saunders, 1950.

36. Rausch, R. "Observations on a cyclic decline of lemmings (Lemmus) on the Arctic Coast of Alaska during the spring of 1949." Arctic, 3; 166-177, 1950.

37. Rausch, R. "Notes on the Nunamiut Eskimo and mammals of the Anaktuvuk Pass region, Brooks Range, Alaska." Arctic. 4; 147-195, 1951.

38. Rikhter, G. D. Snow-Cover, its Formation and Nature. Publishing House of the Academy of Science, USSR. Moscow, 1945.

39. Scholander, P. F., V. Walters, R. Hock, and L. Irving. "Body insulation of some arctic and tropical mammals and birds." Biol. Bull. 99; 225-236, 1950.

40. Scholander, P. F., R. Hock, V. Walters, F. Johnson, and L. Irving. "Heat regulation in some arctic and tropical mammals and birds." Biol. Bull. 99; 237-258, 1950.

41. Scholander, P. F., R. Hock, V. Walters, and L. Irving. "Adaptation to cold in arctic and tropical mammals and birds in relation to body temperature, insulation, and basal metabolic rate." Biol. Bull. 99; 259-271, 1950.

42. Seligman, G. Snow Structure and Ski Fields. London; Macmillan, 1936.

43. Seton, E. T. Life Histories of Northern Animals. New York; Scribner's Sons, 1909.

44. Siple, P. A. and C. F. Passel. "Dry atmospheric cooling in sub-freezing temperatures." Proceedings of the American Philosophical Society, 89; 173-199, 1945.

45. Sharp, R. P. "Ground-ice mounds in tundra." Geog. Rev. 32; 417-423. 1942.

46. Sutton, G. M., and W. J. Hamilton. "The mammals of Southampton Island." Mem. Carnegie Museum, 12; 9-111, 1932.

47. Sutton, O. G. Micrometeorology. New York; McGraw-Hill Book Co., 1953.

48. Taber, S. "Perenially frozen ground in Alaska; its origin and history." Bull. Geol. Soc. Am. 54; 1433-1548, 1943.

49. Wiggins, I. L. "The distribution of vascular plants on polygonal ground near Point Barrow, Alaska." Contributions from the Dudley Herbarium. 4; 41-56. Stanford, Calif., 1951.

50. Wolfe, J. N., R. T. Wareham, and H. T. Scofield. "Microclimates and macroclimates of Neotoma, a small valley in central Ohio." Bull. 41, Ohio Biol. Survey, Ohio State Univ., Columbus, Ohio, 1949.

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