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FINAL REPORT

A RECONNAISSANCE STUDY OF CERTAIN ASPECTS OF THE HEAT CYCLE OF LAKES

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Introduction

In 1957, the Office of Naval Research Geography Branch and the University of Wisconsin Meteorology Department entered into a contract for the study of certain aspects of the heat cycle of lakes. Over the next ten years the scope of the project enlarged to include other aspects of field climatology, especially remote sensing for field climatic purposes. This report will summarize briefly the accomplishments at that decade of collaboration, the effects of which are still being felt in the Department of Meteorology through the stimulus it gave to the development of a strong research program in climatology. Greater detail on the research results will be found in the technical reports of the project, abstracts of which are to be found in Appendix A. Some of the results will be realized for years, however, as bits and pieces of the research find their way into future work of the principal investigators and the work of the many students who participated in the program.

In many respects the impetus for the research initially came from the work of F. Kenneth Hare (1951) who wrote in that early "state-of=the-art" volume called the Compendium of Meteorology that lack of observational data in the Arctic and Sub-

Arctic was an acute problem, and that vegetation and soils are mirrors of the normal climate. He also pointed out that attempts to relate climate and the arctic tree line were up to that time hit-and-miss affairs with no rational basis. The principal investigator had been working on the heat cycles of lakes and had found that in many respects they integrated the climate with fair precision. Looking at a map of central Canada with its million lakes and handful of weather stations, a partial solution to some of the problems posed by Hare seemed possible.

In the following sections the results of the investigations will be discussed under three main headings: field climatology, vegetation studies, and remote sensing.

Field Climatology

The underlying philosophy of field climatology is that nature holds the answers to many climatological questions if the investigator will ask the right questions posed in the right way. There are many examples, though not usually identified as being parts of field climatology. Studies of pollen profiles for paleoclimatic purposes, and many other ecological and paleoecological studies are concerned with the indication of climatic by natural "instruments". Some such indicators are quantitative, some are qualitative, and some could be made quantitative if the correct transfer function could be found to translate biotic, geomorphic, pedological

etc. variables into the familiar variables ordinarily associated with climate. A related type of field climatology is concerned with climatic explanations of certain natural phenomena, where climate is believed to be a factor, or the gathering of specialized types of data for such a study when the normally observed climatic variables are inadequate or inappropriate.

The initial proposal and research efforts concentrated on lakes as climatic indicators for they have spatially constant physical properties such as freezing point, specific heat, albedo, and, within limits, conductivity. It was established for Lake Mendota that the surface temperature at an open lake was an excellent indicator of the mean air temperature of a preceding period of time that probably varied with the size of the lake (TR#2). Since the regional focus of the study was on the North American sub-arctic, the failure of this method when the lake was frozen led to ice investigations. The heat budget of the lake could be estimated even in winter (TR#2) and the time of freezing and thawing were easily observable temperature-related events (TR#3). The heat budgets of other ice-covered lakes were investigated (TR#s 6, 13) and an abbreviated method for calculating the heat content of lakes was developed (TR#39). The freeze-up and thaw studies were extended with low-level photographic aerial reconnaisance (TR#s 10, 20). The freezing of deep lakes was shown to occur when the running mean of the previous 30-40 days reaches $0^{o}C$. Shallow lakes integrate over shorter times and

in central Canada most shallow ponds froze after the three day mean temperature had dropped to zero. It should, therefore, be possible to use high resolution photographic satellite imagery to delineate some mean isotherms over central Canada in the autumn.

During the course of the contract it became possible to measure the surface temperatures of the lakes from the air, in turn making possible the mapping of the mean temperature of the previous month with a single days flight. Infra-red bolometry was used to measure the surface temperatures of over 300 lakes over a north-south range of about 700 miles, and the trends of the isotherms were found to parallel the mean atmospheric isotherms of the previous month (TR#22).

In order to be quantitative about the time interval for which the surface temperature of a lake provides an integrated air temperature it is necessary to know the depth of the lake. In a number of cases, test lakes were actually surveyed by bathometer. The method was too time-consuming and yielded more detail than needed, so a simple method was developed to measure the mean depth of a lake from a map or airphoto and a few hours simple measurement at the seiche period made from shore. Adequately accurate mean depths can be obtained using Merian's formula which relates length, depth, and seiche period (TR#17).

Another more or less homogeneous element of the landscape which was thought to have possibilities as a climatic

indicator is the sphagnum bog. They are very common in the Boreal forest region and represent, in effect, bodies of water held nearly motionless or in laminar flow by a network of sphagnum which is a tiny fraction of the mass of the bog. The distribution of the particular bog surface form which is called "string bog" is in itself climatically related (TR#14) It was shown that, using the theory of heat flux in an homogeneous medium, one relatively shallow single soil temperature profile can yield the same amount of climatic information as that obtained by recording soil temperatures at two fixed depths for a year (TR#23). The annual bog surface temperature variation can be reconstructed from a single mid-summer probe of the vertical temperature distribution in the bog.

Application of the aerial infrared technique to the Great Lakes, specifically Lakes Superior and Michigan, shows that the horizontal variation of surface temperature in these large bodies of water is so great that reliable information on their heat balance cannot be inferred. However, this horizontal variation led to new insights into the circulation of these lakes (TR#s 11, 27 and 29). This work had been continued under the sponsorship of the Office of Water Resources and has yielded significant findings on the seasonal nature of the circulation of Lake Superior.

In the region where most of the field studies were made, Hudson's Bay is a significant climatological factor.

Extension of the infra-red survey technique was therefore made to Hudson's Bay in an effort to clarify the pattern of ice decay during the summer and the patterns of surface temperature are related to the modification of the airmasses crossing the bay. Results are summarized in TR#s 28 and 36.

Still another potential field indicator of climate is contained in the tree ring record. Many papers have indicated that near the tree-line tree growth is controlled by summer temperature. Our studies indicate that even in the barest forest the growth rate is a function of several variables besides temperature, yet regional values of the growth rate decline rather regularly towards the tree line, which can be defined theoretically as the line where the growth rate is inadequate to keep the tree alive (TR#33). Many lines of evidence which we uncovered indicate that biological indicators of climate have gradients normal to the tree-line as are the major climatic gradients.

This last statement suggests one of the major results of the research. The biotic and climatic patterns of central North America must show close parallelism if it is true that the biota or parameters derived from it are climatic indicators. In turn, it is not necessarily the standard climatic parameters that are indicated. IN TR#24, it is shown that if one uses the concepts of the airmass and the airstream that carries it, one may derive a totally genetic pattern of climates with naturally defined boundaries between climatic regions.

It is shown in TR#24, 34, and others that the biotic regions are closely coincident with these genetically derived climatic regions. Since the termination of the contract it has also been shown that about two thirds of the variance of the pollen rain in central North America is covariance with the frequency and duration of airmass regimes.

These close parallels between the biota and the airmass climate open up many possibilities for the interpretation of time-remote climates, since paleontological evidence of past biotic assemblages can be used as indicators of past climates. In TR#21 buried forest horizons in the tundra of Keewatin were used as evidence of past forest climates extending north of the present tree-line. IN TR#34, plant and animal assemblages of late glacial age were used to reconstruct the late glacial climatic pattern. A needed input for this reconstruction and others was a reliable map of the Laurentide ice margin - and none was available in the literature - so it was reconstructed from radiocarbon data (TR#35). Attempts at using standard climatological parameters to interpret the natural climate-related features such as vegetation were less successful. For example, there is some resemblance between gradients on a precipitation map and vegetative boundaries (TR#8).

Although many facets of the heat cycle of lakes and the sub-arctic land surface were explored, including a field measurement of the elements of the heat budget over tundra (TR#37), the mapping of the elements of the heat budget is

still incomplete. Calibration of certain elements of the landscape as indicators of some parts of the heat budget was achieved. Direct measurement of net radiation (TR#19) at several stations plus extensive albedo measurement and development of surface temperature indicators laid a partial framework for a synthetic radiation climatology. The biological studies, described in the following pages, along with many of the studies mentioned above, provide an in-depth study of biota in relation to climate (defined as characteristic climatic complexes).

Characteristics of the Arctic and Boreal Vegetations and Their Relationships to Climate

While it had long been assumed that close correlations exist between regional zonation of native vegetation and climate, there were no very successful efforts to relate the two directly over a large area, utilizing sufficiently detailed quantitative information to provide convincing evidence that the apparent relationships are not only real but also subject to measurement. In a review of the boreal vegetation written by Raup nearly three decades ago, this was cited as being one of the long-standing problems of not only the boreal vegetation but of many of the world's regional vegetations, and a problem which should be both interesting and useful to pursue. It has been the purpose of the research briefly reviewed here to establish the relationships between vegetation and climate in the boreal and arctic regions in a manner which would permit

one to be used as an indicator of the other.

As early as Humboldt, broad relationships between climate and vegetational type (biome, formation, etc.) had been described in general terms, and later climatic mapping such as that of Koeppen and Thornthwaite was based upon a recognition of different regional vegetation types. All of these efforts involved a certain show of faith that vegetation and climate are correlated in some fundamental and ultimately demonstrable manner. The relatively new techniques of vegetational continuum analysis, as well as such analytical tools as factor and principal component analysis, coupled with the newly-developed methods for airmass analysis (TR#24), have provided the means by which detailed studies providing evidence in support of this concept have been conducted.

The area of Canada employed in the study is particularly valuable for investigations of this type because of the general broad uniformity of the land surface, in terms of topography and geological parent materials, which provides a relatively homogeneous substrate over an extensive region. There is, in addition, a striking vegetational zonation in this region, with boreal forest to the south, tundra to the north, and a distinct ecotonal region between the two. The disturbance of the natural vegetation by man is minimal in the entire region, rendering the search for suitable stands of native forest and tundra a relatively easy one. During the course of the work it was shown that there is, indeed, a correspondence

between structural composition of vegetation and variations in climate throughout the region extending roughly northward to the Arctic Ocean from a line drawn from western Ontario to the east slope of the Mackenzie Mountains.

Determinations of vegetational community structure included sampling, using a standardized statistical procedure, at many points throughout the boreal forest and tundra west of Hudson Bay (see Fig. 1). The procedure employed was designed to reveal differences in vegetation from region to region which could then be related to climatic differences. While comparisons between vegetation and climate were designed essentially to reveal basic relationships between the two, it was also recognized that the work might be applied to some practical purpose in the sense that plant indicator species might be recognized which would be of use for delineating general climatic conditions in areas were meteorological data are presently lacking due to the great distances between weather-recording stations. Published reports outlining certain aspects of the work are listed in the bibliography (TR#s 7, 15, 16, 18, 25, 26, 32) and additional publications will be forthcoming.

In the first of this series of Technical Reports, an interpretation of vegetational types by means of aerial photographs was made using the photographs available from the National Air Photo Library of Canada for areas in the boreal forest of western Ontario and Manitoba. For the

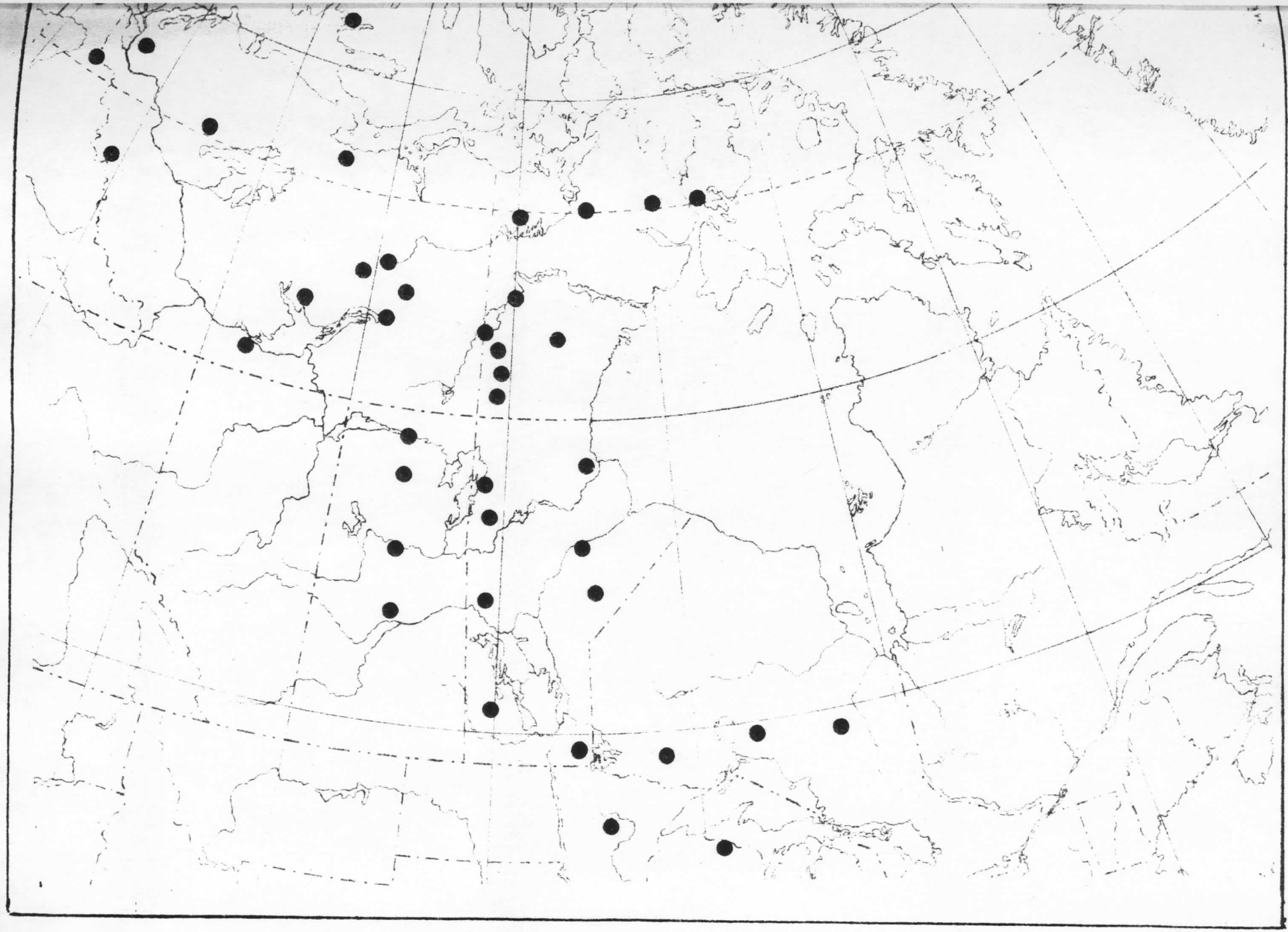

Fig. 1. Dots designate vegetational study areas described in text.

areas employed in the study, comparisons were made in terms of general vegetational composition (primarily on the basis of dominant forest trees), topography, and surficial geology, and the not-surprising conclusion was reached that regional comparisons of vegetation on the basis of aerial photography was impractical without extensive sampling of vegetation on the ground. The difference in the vegetation between one region and another was usually sufficient to preclude the extrapolation of interpretive guides from one region to another; in other words, each region must be analyzed individually on the basis of "ground truth" determined for that region, since differences between regions are so great as to make general rules applying to more than one region difficult or impossible to establish. This made general utilization of aerial photographs in the initial analysis of vegetation quite impractical for the purposes of regional comparisons required in the study and, as a consequence, a program of quite extensive vegetational sampling was undertaken throughout the region of the study west of Hudson Bay. The subsequent Technical Reports and other publications now completed or in preparation deal with the results of this extensive program of vegetational sampling conducted in the central Canadian boreal forest and tundra. Two introductory reports (TR#15-16) were concerned with a compilation and review of the existing pertinent references concerned with the glacial and botanical history of the boreal and arctic flora and with the physiological characteristics

of the northern plant species. The first study was undertaken to assess the importance of post-glacial migration pathways of plant species in determining the present-day distributional patterns. The second was undertaken to review existing evidence that the northern plant species possess a measure of physiological individuality as a consequence of adaptation to the arctic environment and that physiological traits constitute a biological assay, in a sense, of the unique characteristics of the environment in which plants possessing them are found. These studies were undertaken to establish requisite theoretical assumptions that the present-day distribution patterns of the vegetation of the boreal and arctic regions can reasonably be employed as parameters in the bioclimatological comparisons which were to be made.

The known corespondence between the northern limit of trees and certain climatic parameters has long been part of the literature concerned with the northern regions, and the studies undertaken in the Ennadai Lake area (TR#18) represent an effort to delineate more clearly the relationships between plant communities and climate in central northern Canada in the vicinity of the northern forest border. The observations on the environmental relationships and past history of the spruce forest establish the existence of an abrupt vegetational ecotone in this area, corroborating available evidence (such as TR#24) indicating that a rather distinct climatic transition also prevails in the region. Post-glacial history of the forest

was delineated in a subsequent publication (TR#21). An ordination of coefficient of similarity values for stands used in the study indicates that communities are arrayed on a continuum primarily according to (a) topographic position, ranging from low Carex meadow on one end of the x-axis to rock field and esker summit on the other, and (b) along a subarctic-arctic climatic gradient. It is of interest, additionally, that black spruce forest occupies most of the land surface on the south end of Ennadai Lake, but is confined to rather special ravine and lowland habitats at the north end, indicating that here in a span of about 50 miles the environment becomes inimical to the survival of spruce over the greater part of the land surface. Climatic factors must be responsible since topography and geology are generally uniform over the entire region. Fossil podzol soil profiles and charred remnants of Picea or Larix discovered at the north and south ends of Ennadai Lake, and extending northward to Dubawnt Lake, indicate that at one time the spruce forest extended farther northward than it does at the present time. Relationships between the plant communities at Ennadai, Dubawnt, and Yathkyed Lakes corroborate the conclusion that plant community structure over this region reflects the known climatic gradients and that these communities can be employed as climatic indicators.

Using data obtained from soil samples that had been collected at a number of study sites in the boreal forest, another study was undertaken to further establish the theoretical basis

of the assumption that regional variations in vegetation are a consequence primarily of climatic differences and that conditions of the substrate throughout this region have at best a secondary role in determining vegetational distribution patterns. This study (TR#25) also afforded the opportunity to compile an extensive review of the podzol soils and their mode of formation and relationships to plant growth and species distribution. With the assumption at least fairly well established that climate is a principal determinant of the regional variations in vegetation, the theoretical basis had been laid for the subsequent Technical Report (#26) in which regional differences in understory vegetation in the boreal forest of principally Ontario and Manitoba were shown to have strong relationships to regional climatic differences. In this study, four major vegetational community types in the region encompassing western Ontario, Manitoba, eastern Saskatchewan, southern Keewatin, Minnesota, and Wisconsin were sampled. The data indicated that climatic or climatically-related environmental influences are of sufficient magnitude to result in discernable correlations with plant community differences, using techniques of ordination of coefficient of similarity values and statistical treatment by means of factor analysis. Species groups responding most strongly to climatic differences were identified. It was apparent that meaningful correlations could be discerned between plant community differences and specific climatic parameters. A subsequent study (described in TR#32) showed that

the rather striking vegetational zonation found along north-south axes through the forest-tundra ecotone also possesses a close relationship to climate. Some of the possible climate-vegetation relationships were discussed. In this forest-border ecotone, specifically the ecotone in the region extending from the forest border at the south end of Ennadai Lake northward to Dubawnt Lake, some 150 miles distant, is characterized by floristically depauperate communities in the region immediately adjacent to the forest border and by an increasing number of typically arctic species northward. This increase in richness of arctic components in the vegetation appears related to the increasing prevalence northward of habitat conditions associated with Arctic air masses, since other factors such as topography, surficial geology, and soil parent materials seem relatively uniform throughout the region, and since sufficient time apparently has elapsed since the most recent climatic fluctuation to permit species to migrate to the geographical limits of their environmental tolerances. North of the mean summer position of the arctic front is to be found an increasing number of arctic species; it appears possible to define the position of the arctic frontal zone in terms of plant community structure. The region of greatest frontal disturbance is a depauperate zone, north of which there is an increasing frequency of arctic species in the plant communities. Other parameters related to plant growth were also rather closely related to the zone characterized by the summer position of the arctic

front. It was shown in the work in the boreal forest proper and at Ennadai Lake that black spruce growth rates declined steadily northward from the central boreal forest to the northern forest border (TR#18) and this relationship was further explored by Mitchell (in TR#33) who shows that the isolines of black spruce growth rates run parallel to the forest border and that it is possible to define a theoretical tree line on the basis of the decline in growth rate northward.

The work establishing the frequency of various air mass regimes throughout the area of the vegetational study (described in TR#24) has provided a climatic complex foundation upon which to base correlations between climate and the frequency values of the various species found in the plant communities sampled throughout the study region. This work is continuing and further publications are anticipated concerned with the delineation of the relationships between plant species frequencies and air mass frequencies. The techniques of factor and principal component analysis have been used extensively in these exploratory efforts to determine the relationships between vegetation and climate.

A rather broad spectrum of possibilities remains for further analysis of data obtained during the course of the field sampling of plant communities throughout the central and western interior plains of Canada (as well as data from Ungava now available). There is, moreover, a variety of climatic data now also available, in addition to the air mass data mentioned, which

has accumulated as a consequence of the general program conducted under this contract. Some of this additional climatic data might be mentioned for illustration: climatological data, for example, were obtained during the course of the work in a number of ways, including year-around acquisition of lake temperature profiles at many of the study sites shown in Fig. 1. Other data also includes a record of the chronology of break-up and freeze-up of Canadian lakes during spring and fall seasons, studies of bog temperatures and other natural climatic phenomena, studies of the summer radiation balance and energy budget of the Canadian tundra, (all mentioned in the preceding paragraphs) and studies of a number of other aspects of the bioclimatology of the region, some of which are listed in the bibliography at the end of this report.

It might be said in summary that it is apparent that individual species can be used for generalized delineations of the airmasses characteristic of the more remote regions of Canada in which meteorological stations do not exist and for which climatological information is largely lacking. The central northern interior plains of Canada afford an excellent site upon which to make such inferences because the native vegetation is in a virtually natural and undisturbed condition, the soil and topographic variations are at a minimum, climatic differences between areas are maximal because of the great distances involved. Perhaps no other region on earth could afford the opportunity for work of this type.

Identification of those species which appear most sensitive in their responses to climatic parameters is of interest additionally because these species can now be grown in controlled environmental chambers to study their physiological response to various climatic factors. A detailed knowledge of the physiological responses of these species and of their tolerance limits should permit a rather exact description of the environment. It is of significance, in this regard, that detailed microclimatological investigations were conducted over the Arctic tundra during the summer of 1966 in conjunction with the vegetational studies. (TR#37).

Data permitting an altitudinal check on the wide-ranging latitudinal and longitudinal data have also been obtained. It is known that there are similarities between latitudinal and altitudinal timberlines; work was conducted on the east slope of the Mackenzie Mountains and data obtained which can be compared to the data obtained in the interior plains. In the interior plains, variations in vegetational community structure occur only over relatively long distances. By employing the slope of the Mackenzie Mountains as an altitudinal gradient, it was found that here the vegetational zonation corresponds in certain specific characteristics to the latitudinal zonation found along the south-north gradient in the continental interior. This correspondence makes it possible to delineate more clearly the specific climatic parameters involved in vegetational differences from one place to another, and to elimin-

ate the possibility that photoperiodic or edaphic responses are critically limiting the range and performance of various plant species employed as indicators.

Additionally, it should be pointed out that the vegetational data now available for a large number of the study sites indicated on Fig. 1 represent the initial vegetational and ecological survey of the area. Although botanical exploration has been adequate throughout most of northern Canada and provides a good outline of the species present in the region, quantitative information on species relationships in even the most prevalent and ubiquitous plant communities had never before been obtained. For the study sites indicated on the map, this has now been accomplished. The data, moreover, is in a form suitable for statistical analysis by the most sophisticated techniques. Statistical analyses of the data available are now being undertaken and this work will continue. It is now possible, using these data and additional information on terrain and topography, to provide a systematic environmental summary for this region which will afford a significant contribution to understanding the natural geography of the Canadian Subarctic and Arctic regions. The information now available is to be incorporated into an environmental summary describing the following general aspects of climate, terrain, and vegetation:

1) Relationships between vegetation and climate throughout the boreal forest region, the forest-tundra transition, and

the continental Arctic tundra of Northern Canada.

2) Vegetational indicators of airmass regimes, permitting climatic descriptions for areas lacking meteorological data by means of vegetational analyses;

3) Detailed characteristics of the vegetational communities in various designated subregions, with descriptions of these communities and variations within them due to variations in terrain, topography, and surficial geology;

4) Interpretation of vegetation and terrain features from aerial photographs of representative regions;

5) Interpretation of visibility and density characteristics of natural vegetation in representative areas from climatic data and aerial photography;

6) A generalized systematic categorization of the subregions based on climate, vegetation, and the physical characteristics of the terrain, to provide a rational regionalization of the areas studied.

Remote Sensing

Throughout the study the emphasis was on the development of sensitive climatic indicators which could be rapidly surveyed to provide climatic data in regions of sparse standard observations. This naturally led to concern with rapid survey techniques which might yield information on either the distribution of climatic indicators or of the pertinent climatic parameters themselves. This general area of investigation is now

subsumed under "remote sensing". A prime concern in remote sensing is the behavior of the instrumentation itself and a concern with precisely what is sensed. From aircraft flying over an area, remotely sensed ground parameters are "seen" as area averages distorted by the motion of the aircraft (TR#1). The value sensed is also often dependent on attenuation by the atmosphere beneath the aircraft. Some of these errors may be corrected by using both narrow-band and broad-band sensors (TR#30) or multi-band sensing (TR#31). Sometimes a correction must also be applied for the emissivity or reflectivity of the surface being sensed (TR#19).

Incomplete Studies and "Targets of Opportunity"

As with most broad research programs, some of the studies undertaken failed to achieve meaningful results or turned out to be incorrect in basic promise, yet may produce worthwhile intermediate results. The total failures are rarely reported. One study that was started but not carried to completion was based on the idea that the thermocline depth might be a measure of the preceding wind conditions over a lake. In the course of the investigation however, some excellent information was obtained on wind driven currents in a lake and their vertical variation. These results are summarized in (TR#s 4 and 5).

It was inevitable that with thousands of miles of travel over relatively unknown areas, certain phenomena would be observed which were not directly related to the purpose of the

study but which are worth reporting. One such was the peculiar distribution of waves on a very large cold lake with overrunning warm air (TR#9). Instead of the waves increasing with increasing fetch, they were observed to diminish as the air became more stable in crossing the lake. Another such observation was of shallow arctic lakes with mud flats occupying their centers but not their margins (TR#12). It now appears that this is a transient phenomenon of the spring, the frozen mud of the bottom floating to the top after the ice has thawed, for the mud centers soon disappear after reaching the surface and the sediment, well stirred, drops again to the bottom. This of course has considerable impact on one's interpretation of pollen profiles from the bottoms of arctic lakes.

The most important incomplete study started by the research group working under Nonr 1202(07) developed from their particular combination of skills, equipment, view points, and interests. This was an investigation of the ecological and climatological implications of mineral particulates suspended in the atmosphere over northwest India. It was believed that the dust was sufficiently dense to affect the radiation transfer through the atmosphere and that with aircraft and remote sensing this effect could be studied. With Navy assistance, a field expedition to India was mounted and data on radiation transfer and dust density was collected. It was indeed shown that the dust changes the infrared fluxes in an entirely unexpected way. Details are given in Technical Report #38.

Summary

The basic purpose of the research, to establish the relationships between terrain, vegetation, and climate in central North America, was realized in large measure. There remain many, many research problems, but a much deeper understanding of the boreal and subarctic environment has been achieved. Numerous dissertations have been supported by this work, and the students trained in connection with the project will continue to extend its effect for many years. It is also fair to say that the ONR-University of Wisconsin collaboration assisted greatly in the establishment of the Center for Climatic Research and Marine Studies Center of the University.

Appendix A

Abstracts of Technical Reports Submitted Under Contract Nonr 1202(07)

1. Dutton, J. A. "Space and Time Response of Airborne Sensors for the Measurement of Ground Parameters" September, 1959

Abstract: Mathematical relationships between true values of ground variables and values recorded by radiation-sensitive instruments mounted on an airplane in horizontal flight are given. Both temporal and spatial distortions are considered; atmospheric depletion is not. Instruments now in use on an airplane are described to provide specific illustrations. It is shown that measurement of space averages is possible, and weighting functions which affect the recorded values are exhibited for both narrow- and wide-beam instruments. A tractable analysis of the characteristics of wide-beam instruments requires assumptions about the homogeneity or antisymmetry of the ground variable. Measurement of variations in small areas is shown to be difficult with standard instruments. Weighting functions are derived which allow reconstruction of the variance and cross spectra of ground values from the spectra of the recorded values. The development suggests important factors in flight planning and yields methods of error analysis.

2. Dutton, J. A. and R. A. Bryson "Heat Flux in Lake Mendota" January, 1960

Abstract: The physical processes of heat transfer at the lake's surface and the internal heat flux are studied for the "average" Lake Mendota and for 1958-59. The surface heat budget is determined quantitatively. Details of the internal fluxes of the heat supplied or lost at the surface are discussed, with emphasis on the effects of wind stirring and hydrostatic stability. It is shown that a well-known solution to Fourier's heat conduction equation suffices to describe many of the features of the internal temperature range and heat flux when an effective thermal diffusivity is introduced.

The solution is further used to demonstrate that the internal seiche along the thermocline causing heat flow in bottom sediments may account for 40% of the heat transfer to the hypolimnion.

3. Ragotzkie, R. A. "Compilation of Freezing and Thawing Dates for Lakes in North Central United States and Canada" September, 1960

Abstract: The freezing and thawing dates of some lakes in Wisconsin, Minnesota, Michigan and Canada are summarized. These meteorological proxies represent an integrated time series of a number of climatic parameters. Although some of the records are only a few years in length, a number are over one hundred years long.

4. Shulman, M. D. and R. A. Bryson "The Vertical Variation of Wind Driven Currents in Lake Mendota" July, 1961

Abstract: The deviation of wind-driven water currents from wind direction was examined as a function of depth in Lake Mendota utilizing the free-drag method. The mean vector hodographs were obtained for various wind velocities. The relation of wind velocity to angular deflection was also obtained.

The depth of frictional influence was empirically determined to be between 2 and 3.5 m and an improved relationship with wind speed was developed.

Wind stress on the water surface was calculated by fitting Ekman and Rossby spirals to the hodographs and integrating the cross-wind component from the durface to depth D. The proportionality of the stress to the wind velocity was determined and comparisons made with previous computations.

5. Haines, D. A. and R. A. Bryson "An Empirical Study of Wind Factor in Lake Mendota" July, 1961

Abstract: Wind blowing across a water surface will transmit momentum to the water and cause a surface current. The ratio of water velocity to wind velocity is called the wind factor. This paper presents observed values of the wind factor obtained as median values and by regression analysis of wind velocity vs. water velocity. The data show that the wind factor is a discontinuous function at a critical wind speed. Water velocity in the surface layers increases with wind velocity until a critical wind speed is reached, and then it decreases.

This observation is in agreement with Munk's (1946) theory of a critical wind speed for air-sea boundary processes, which yields air-sea boundary instability for winds exceeding 6.5 m/sec. The observations taken in Lake Mendota yield a critical wind speed of 5.7-6.1 m/sec. The present results were arrived at after a study of 356 observations.

6. Scott, J. T. and R. A. Ragotzkie "Heat Budget of an Ice Covered Inland Lake"
October, 1961

Abstract: The heat budget for Lake Mendota in evaluated for two winter seasons. Winter is defined as extending from the time just before freezing of the lake surface until all ice has melted in the spring. Change in heat storage, radiation flux, conduction (molecular and/or eddy) and advection are determined separately for snow, ice, and water where applicable. Sensible and latent heat flux at the lake surface are not directly measured, but the heat budget method appears to be promising for determining at least their sum.

Aerial and lake surface measurements of albedo are compared with each other and to visual estimates of albedo based on ice or snow conditions and age of the snow surface. Results indicate that visual estimates by experienced observers are reliable to within 10 percent.

Heat conduction in the snow-ice-complex is measured using a thermocouple and flux-plate assembly.

Seven distinct periods of the winter season are described using the heat budget data for the two years. Net radiation, air temperature, and amount and type of snow cover are the most important factors affecting the heat budget of the winter lake.

7. Larsen, J. A. "Major Vegetation Types of Western Ontario and Manitoba from Aerial Photographs"
February, 1962

Abstract: Major vegetation areas are deliniated from aerial photographs for the following areas: Remi Lake area, Klotz Lake area, Raven Lake area, West Hawk Lake area, Riding Mountain area, Rocky Lake area, Ilford and God's Lake area, and Lynn Lake and Brochet area.

In addition to a description of the forest vegetation assemblages, brief summaries of surficial geology and trafficability are presented. The interpretive technique is discussed and a limited number of references for each area are given.

8. Sabbagh, E. and R. A. Bryson "An Objective Precipitation Climatology of Canada"
April, 1962

Abstract: The seasonal and regional distribution of precipitation over Canada is presented by means of variance components or harmonics. Precipitation regimes are identified and characterized. Certain significant features of the annual march of precipitation are explained in terms of the atmospheric circulation. Associations between precipitation patterns and natural vegetation and water bodies are investigated.

9. Ragotzkie, R. A. "Effect of Air Stability on the Development of Wind Waves on Lakes"
September, 1962

Abstract: Two series of aerial and surface observations of lakes in Canada are presented in which wave formation depended on the stability of the air over the water. In the first set of observations a cold, deep lake remained mirror-smooth under wind conditions that developed gravity waves 4-6 in. high on nearby warmer, shallow lakes. The second observation is of Dubawnt Lake, a large, cold, arctic lake, where wind waves developed only in the lee of the upwind shore and of islands and disappeared a mile or less downwind. Great stability of the air over the lakes leading to reduced surface stress results from warm air flowing over very cold water.

10. Ragotzkie, R. A. and J. D. McFadden "Operation Freezeup: An Aerial Reconnaissance of Climate and Lake Ice in Central Canada"
November, 1962

Abstract: An aerial reconnaissance of lake ice conditions in Manitoba, western Ontario, Minnesota, and Wisconsin was conducted during the period 24 October to 10 November 1961. Albedo measurements and cloud observations were also made on the flights. As the lake freezing zone migrated southward it grew wider in north-south extent.

This zone, where some lakes were frozen and some open, was characterized by extremely variable albedo and by persistent low cloud and convective activity. The climatological significance of these findings are examined.

11. McFadden, J. D. and R. A. Ragotzkie "Aerial Mapping of Surface Temperature Pattern of Lake Michigan" February, 1963

Abstract: Surface temperature gradients of Lake Michigan were remotely sensed on 7 July 1962 using a Barnes bolometer mounted in a Navy P2V aircraft. Although actual water temperatures are unknown, the surface gradients are clearly shown. The problem of obtaining a true synoptic pattern in minimum time without the loss of detail is discussed.

12. Bryson, R. A. and R. A. Ragotzkie "Mud-Center Tundra Lakes" January, 1964

Abstract: Shallow lakes were observed in the Hudson Bay lowland with central mud flats separated from the shore by nearly complete moats extending along the shore.

13. Scott, J. T. "A Comparison of the Heat Balance of Lakes in Winter" April, 1964

Abstract: Study of fifty-three lakes in Wisconsin during the winter of 1962-63 shows that differences of lake morphometry produce large lake-to-lake variations in many of the heat balance terms and in ice phenology. Lake depth and size are the most significant morphometric features influencing heat balance and phenology. Differences in lake morphometry produce a larger variation in ice thickness in one area than a latitude difference of 250 miles.

The mean temperature of the water on the lake closing date and maximum ice thickness are significantly correlated with mean fetch of the lakes. A multiple regression analysis shows that mean depth is not significantly correlated with these two factors. Lake depth influences the change in mean temperature of the water, especially during cooling and for a short period after opening.

Shallow lakes close before deep lakes. Opening date is influenced by both size and depth of the lake.

Large lakes have the greatest rate of increase in ice thickness in mid-winter. Maximum ice thickness for a particular region is found on lakes of greater than 1.5 km mean fetch provided the mean depth exceeds 4 m. Thinner ice is found on smaller lakes and lakes of less than 4 m mean depth. Ice thickness may decrease on very shallow lakes during periods when it increases rapidly on deep lakes.

A detailed comparison of the heat balance of nine lakes shows that lake-to-lake differences in maximum ice thickness of as large as 20 cm are most probably produced by differences in heat flow from the water to the ice and exchange of heat with the atmosphere. Heat flow from the water to the ice is affected by both lake size and depth because both of these factors influence water temperature. Heat gain from the atmosphere in mid-winter was greater the smaller the lake. This is attributed to a higher albedo of the lakes than of the surroundings. Radiation absorbed by the surrounding forests is advected to the lakes producing the largest effect on lakes with large shoreline to area ratios. Variations in snow depth caused by drifting may also influence heat exchange with the atmosphere. Greater variability of snow depth on large lakes may allow for greater heat loss when large-scale advection is influencing the lakes.

The magnitude of heat flow from the water to the ice computed by assuming molecular conduction immediately below the ice agrees fairly well with heat flow computed by difference from the heat balance of the water. This indicates that there is practically no turbulence in the upper layers in ice-covered lakes.

The lakes are good climatic indicators provided morphometric factors which produce non-climatic effects are taken into account. Maximum ice thickness and ice phenology data are useful climatic indicators.

14. Knollenberg, Robert "The Distribution of String Bogs in Central Canada in Relation to Climate"
August, 1964

Abstract: String bogs in central Canada were found to have maximum development in the mid-boreal forest zone. Analysis suggests that they are found in the region of maximum depth of freeze and thaw penetration.

15. Larsen, J. A. "An Outline of Materials for a Postglacial Bioclimatic History of Keewatin, N.W.T., Canada" August, 1964

Abstract: This paper is a compilation of existing pertinent references and citations from literature concerned with the glacial and botanical history of the Arctic, and particularly of central Canada, since the close of the Tertiary, and with some interpretations of the more recent period in light of the presently available information.

16. Larsen, J. A. "Role of Physiology and Environment in the Distribution of Arctic Plants" November, 1964

Abstract: A review of literature concerned with the physiology of arctic plant species, undertaken as part of investigations of arctic plant communities and their relation to regional climate. Since a basic tenet of this research on arctic bioclimatology is the assumption that vegetation reflects the environment, it seemed advisable to establish the requisite theoretical foundation by obtaining evidence that arctic species do possess physiological individuality as a result of their adaptation to the arctic environment, and that these physiological adaptations do constitute a measure of the unique characteristics of the habitats in which these plants are to be found.

17. Stewart, Ronald "On the Estimation of Lake Depths from the Period of the Seiche" December, 1964

Abstract: Seiche periods on a group of Wisconsin lakes were measured in an effort to verify Merian's formula for estimating mean depths. On the basis of this study, the use of Merian's formula provides an estimate of mean depth with an error of less than 1 m for lakes that vary between 2 and 30 m in mean depth.

18. Larsen, J. A. "Vegetation of the Ennadai Lake Area, N.W.T.: Studies in Subarctic and Arctic Bioclimatilogy I" January, 1965

Abstract: Correspondence between the northern limit of trees and certain climatic parameters is a well-established ecological concept; this study represents an effort to delineate more clearly the relationships

between plant communities and climate in central Northern Canada. Analysis of plant communities in the region of treeline at Ennadai Lake, Northwest Territories (61°N, 101°W), and observations on the environmental relationships and past history of the spruce forest establish the existence of an abrupt vegetational ecotone in the area, corroborating available evidence which indicates that a rather distinct climatic transition also prevails in the region.

19. Finke, Denford D. "A Correction for the Net Radiometer Reflection Error" and
Wendland, Wayne M. "Analysis of Measured Net Radiation Values for Canada"
July, 1965

Abstracts: (1) A correction factor is developed to convert measured radiation values obeained from a net radiometer to the net radiation for a lake based on the reflectance difference of water and polyethylene surfaces. The daily mean emitted upward radiation of lake and land surfaces are assumed equal. The downward directed radiation from the sky and sun over both land and water surfaces are also assumed equal. Therefore, the differences in the albedo and emissivity of the interface surfaces of land, polyethylene and water are the determining factors causing a difference in the net radiation of each body.

Formulae are presented to calculate the reflectance of a polyethylene and water surface given the angle of incidence of the solar beam (date and time). The differences between polyethylene, water, and land are readily calculated. Since this correction is applied only to direct solar beam, measurements of this flux are desired. However, calculated values are useable, and methods of such calculation are discussed.

The correction factor for the economical radiometer is larger in magnitude than the factor for a ventilated type net radiometer. The factor is a maximum for large sun angles and approaches zero as the sun angle approaches zero.

(2) Daily, monthly, and annual values of measured net radiation were calculated for four central Canadian sites for the period 1960 through 1963.

These values are compared with the calculated estimates of Simpson, London, and Budyko, and with measured values recorded by the Meteorological Branch, Department of Transport of Canada for five other Canadian sites.

No simple direct relationship was found between net radiation and latitude. The measured net radiation gradient is directed normal to the tree line, and stations in areas of similar plant communities report similar net radiation regimes.

Relationships between net radiation and mean daily cloud cover are investigated. The technique of Fourier analysis is used to study the asymmetry of the annual net radiation curves.

20. McFadden, James D. "The Interrelationship of Lake Ice and Climate in Central Canada"
July, 1965

Abstract: An aerial reconnaissance of lake ice conditions in the Shield region of central Canada west of Hudson Bay, and northeastern Minnesota and Wisconsin was conducted during the periods of lake freeze-up 1961 and 1963 and lake break-up 1963 and 1964 using a P2V patrol aircraft provided by the United States Navy. Albedo measurements of the surface were also made during these flights. The data from these surveys were compared with climatic data of the region, and the following interrelationships were found.

Observations of the freezing of lakes showed that between the area of all frozen lakes and the area of all open lakes ther is a transition zone. The southern boundary of this zone is determined by the freezing of the shallowest lakes and the northern boundary by the freezing of the deepest lakes. The width of this zone and the directional trend and movement of its boundaries showed a recognizable pattern from year to year for the same region. These patterns reflect and are apparently related to het climatic singularity "Indian Summer".

The patterns of ice break-up for 1963 and 1964 could not be directly compared because different areas were investigated, but the transition zone was observed to be narrower and better defined in the northwest section of the study area, indicating that the climatic boundaries are also more distinct toward

the northwest. This agrees with the more sharply defined vegetative boundaries found in this region.

Comparison of lake freezing dates with running mean air temperatures shows that there is good agreement between the freezing date of deep lakes and a 40-day running mean air temperature of 0°C., and a fair agreement between freezing dates of shallow lakes and a 3-day mean air temperature of 0°C. The agreement between thawing dates and mean air temperature is relatively poor.

Aerial measurements show that there is very little horizontal variation in the albedo of the tundra in the summer when lakes are free of ice and in the winter when they are frozen and the region is snow covered. Large horizontal variations of albedo occur in the tundra when lakes are frozen but there is no snow, and in the boreal forest region when the lakes are frozen and snow covered.

The rapid disappearance of the snow from the tundra observed in 1963 produced a sudden increase of 600 percent in the amount of absorbed radiation at the surface. A heat budget estimate for the tundra land surface after the snow had disappeared indicates that the sensible heat transfer to the atmosphere was sufficient to heat the lower 1,000 meters of air at a rate of 1.6°C. per day, a figure that agrees quite well with actual observations.

The freezing of lakes does not appear to be dependent on the presence of a particular type of air mass. Sufficiently cold air temperatures to freeze all lakes can be present in an air mass of polar origin, or in an air mass of Pacific origin that has been modified over an extensive snow surface.

Because the freezing date of a lake is dependent on its mean depth, the relative depths of a group of lakes can be estimated from the sequence of their freezing dates.

21. Bryson, R. A., W. N. Irving, and J. A. Larsen "Radiocarbon and Soil Evidence of Former Forest in the Southern Canadian Tundra"
July, 1965

Radiocarbon dating of charcoal on podzols along a transect reaching 280 kilometers north of the present tree line from Ennadai Lake indicates that former forests were burnt about 3500 years ago and again about 900 years ago. These forests probably were associated with periods of relatively mild climate.

22. Peterson, J. T. "On the Distribution of Lake Temperatures in Central Canada as Observed from the Air" December, 1965

Lake surface temperatures in central Canada were observed from the air with an infrared thermometer during spring and fall of 1963 and 1964. The surface temperatures of up to 300 lakes, separated by as much as 700 miles, were obtained on each of several days. The relation between these observed temperatures and meteorological, morphological, and geographical parameters was investigated.

Using multiple regression equations, the temperature data were represented as a function of latitude (ϕ), ϕ^2, $\cos\phi$, longitude (λ), λ^2, size (S), and S^2. The computed isotherms of lake temperature were generally oriented northwest-southeast, in a pattern similar to the mean air temperature isotherms for the previous month. The regression surfaces also showed that the strongest gradient of lake surface temperatures was near the zone of frozen lakes.

The fetch and depth of a lake were both found to influence lake surface temperatures, i.e. large, deep lakes are colder than small, shallow lakes in spring and warmer in fall. Linear regression analysis implied that fetch alone is a relatively poor predictor of surface temperature. The relation between mean depth and lake surface temperature appeared to be non-linear.

Large diurnal changes and the effect of the wind on lake surface temperature were observed during spring and fall.

23. Lettau, Bernhard "The Use of Sub-Arctic Bogs as Natural Climatic Indicators" January, 1966

Abstract: The physical interaction of the atmosphere and

the ground surface has been investigated in a particular attempt to derive climatic temperature values from a very limited amount of observed soil temperature data. A model is proposed in which the Fourier equation pertaining to the sinusoidal variation of temperature in a homogeneous medium has been used to generate soil temperature profiles.

The temperature profile prescribed by the model is an exponentially damped cosine function in the vertical direction with its shape determined by three parameters: the mean annual soil temperature, the surface temperature amplitude, and the thermal diffusivity of the ground. Since the model is non-linear with respect to the parameters, and normal least squares techniques may not be used, and alternate statistical method of determining a set of least squares estimates of the parameters is developed. The agreement between the observed and statistically generated temperature profiles is examined for a number of cases in bogs in the north central United States and Canada. Sphagnum bogs were chosen because they are nearly vertically homogeneous, and because they represent a land form common to a broad latitudinal range.

It is concluded that the values of the three parameters that are estimated by the model are physically valid. Furthermore, it is shown that the amount of information obtained from a single soil temperature profile is equivalent to that obtained by recording soil temperatures at two fixed depths over a period of a year.

The effects of a winter snow cover, frozen ground, and non-homogeneous ground material on the observed temperature profiles, and the implications of the estimated parameters with regard to the annual course of the air temperature are evaluated and discussed. It is found that an extensive winter snow cover will alter the observed temperature field in the ground such that the boundary conditions of the Fourier equation are no longer satisfied.

The estimated annual course of temperature at the ground surface agrees well with the observed air temperatures at nearby stations during summer, but exceeds the observed air temperature appreciably in winter. Based on the cases studied, it can be assumed, however, that the estimated parameters accurately represent t

temperature field within the ground. This technique, therefore, has important applications in the field of phytoclimatology. With respect to temperature variations, sphagnum bogs have been shown to serve very well as natural climatic indicators.

24. Bryson, Reid A. "Airmasses, Streamlines and the Boreal Forest"
February, 1966

Abstract: The analysis of July airmass frequency distribution over Canada is analyzed by daily computation of trajectories from grid intersections back to source regions. A zone of rapid transition from Arctic air dominance to Pacific air dominance is found to lie along the northern border of the boreal forest, suggesting that the summer airmass distribution might be an important causal factor for the distribution of forest versus tundra.

An independent analysis of July airmass frequency distribution by resolution of the daily maximum temperature frequency distribution into partial collectives (component normal distributions) yields results very similar to the trajectory analysis but with more detail. This analysis suggests that airmass dominance might be of importance to other biotic regions as well as the boreal forest and tundra.

A final analysis using monthly resultant wind streamlines near the surface indicates that mean airstreams and confluences between airstreams define climatic regions with a distinctive annual march of airstream (and in the mean, airmass) dominance. These regions show a clear congruence with several major biotic regions. These analyses strongly suggest that the boreal forest occupies the region between the mean (or model) southern boundary of Arctic air in winter and the mean southern boundary of Arctic air in summer.

25. Larsen, James A. "Soils of the Boreal Forest: A Preliminary Survey"
March, 1966

Abstract: Basic soil types and the soil-forming processes at work in the boreal forest zone of Canada are described employing as sources the publications existing in this field. Included are descriptions of the great soil groups found in the region, their differences, similarities, and genetic relationships;

a general description of the chemistry of the podsoliation processes; a review of the more abundant rock types from which the parent materials of the soils in the various areas are derived. Nutritional and ecological relationships of plants making up the vegetative cover on various soil types are described briefly. Included are original data from analyses of soil samples obtained during ecological and bioclimatological studies of the vegetation in areas of Ontario, Manitoba, Wisconsin, Minnesota, and Keewatin, conducted by the author.

26. Larsen, James A. "Relationships of Central Canadian Boreal Plant Communities: Studies in Subarctic and Arctic Bioclimatology, II"
April, 1966

Abstract: Four major vegetational communities in the region encompassing western Ontario, Manitoba, Saskatchewan, southern Keewatin, Minnesota, and Wisconsin were sampled (where available) for the purpose of determining whether regional vegetational community relationships are correlated with regional climatic relationships. Climatic or climatically related invironmental influences are of sufficient magnitude to result in discernable correlations with community differences using the techniques employed in this study, despite the recognized variability in statistical control of the non-climatic variables. Pertinent community relationships are revealed and the species and species groups contributing most importantly to these relationships are identified. The possibilities of achieving meaningful correlations between community differences and specific climatic parameters are discussed with a view to future work.

27. Ragotzkie, Robert A. and Bratnick, Michael "Infrared Temperature Patterns on Lake Superior and Inferred Vertical Motions"
June, 1966

Abstract: A series of aerial temperature surveys over Lake Superior in late July, 1964 showed two areas of cold surface water dominating the surface temperature pattern. Surface water temperatures of 5-6°C. in eastern Lake Superior and 8-9°C. in the western part of the lake were consistently observed. A survey of the literature has provided evidence that these cold areas are a regular feature of the lake. A model is proposed which explains the persistence of these cold areas as a balance between radiational heating of the surface layers and upwelling of colder water from below. A calculation based upon the model indicates

a vertical velocity of 4.5×10^{-3} cm/sec. The relation between the calculated vertical motion and the general circulation of the central portion of the eastern basin is suggested.

28. Wendland, Wayne M. and Reid A. Bryson "Aerial Survey of Hudson Bay Surface Temperature-1965" July, 1966

Abstract: Airborne temperature surveys of Hudson Bay were accomplished on 8 August 1965 and between 22 and 24 September 1965. The temperature of the surface water was remotely sensed with a Barnes IT-2 Infrared Thermometer, and radiation components were measured with a Suomi-Kuhn net radiometer and Kipp and Zonen solarimeters.

The northern part of the Bay cooled about 5^{o} C from August to September. In September, the surface water temperatures ranged from slightly more than 5^{o} C to slightly less than zero. The temperature pattern showed a cold water tongue extending southward along the western shore. A relatively warm arm extended from Cape Churchill to the northeast part of Hudson Bay. A relatively cold protrusion extended southward between Coats and Mansel Islands in the northeastern part of the Bay. The east-central portion was dominated by a rather large (about 6,000 square miles) cold area with temperatures less than 1^{o} C.

29. Ragotzkie, Robert A. "The Keweenaw Current, a Regular Feature of the Summer Circulation of Lake Superior" August, 1966

Abstract: Infrared radiometer surveys of Lake Superior during the summer of 1964 and 1965 have shown that a band of warm water separated by a sharp thermal gradient appears along the north coast of the Keweenaw Peninsula in late June and persists at least into August. The sub-surface thermal structure in this region indicates a steep slope of the geodynamic surfaces with the pressure gradient directed offshore. Calculation of current velocity based on the geo-dynamic slopes gives velocities up to one knot. Direct observations confirm the existence of this current both with regard to location and estimated velocity. The current, for which the name "Keweenaw Current" is suggested, flows northeastward along the north coast of the Keweenaw Peninsula. It appears to

be a boundary current and is probably maintained by the piling up of warm water along the south side of the lake by Ekman transport.

It is shown that although the "thermal bar" effect may exist in early June, this phenomenon does not provide an explanation for the temperature and circulation pattern observed later in the season.

Analysis of infrared radiometer data at intersections of flight tracks on a single day gave diurnal heating rates of 0.21 to 0.27° C. $hr.^{-1}$.

30. Kuhn, P. M., R. A. Ragotzkie and V. K. Menon "Double Bolometer Measurements of the Effects of Atmospheric Radiators"
January, 1967

Abstract: The feasibility and testing of an air-borne, double bolometer (radiometer) technique for deriving atmospheric water vapor profiles at modest cost is illustrated. To achieve these results with "shelf" equipment, the radiative transfer equations are solved for the water vapor transmissivity at aircraft holding levels using observed upward irradiances as input data. The transfer solutions are obtained from computor programs developed specifically for this purpose.

Results indicate an accuracy at least as good as that of the standard sounding electrical hygrometer but with measurements obtained at levels much higher than those at which hygrometer observations are possible. The implications for use on high-flying jet or special purpose aircraft or on rockets are presented.

31. Menon, V. K. and R. A. Ragotzkie "Remote Sensing by Infrared and Microwave Radiometry"
February, 1967

Abstract: In part I, the basic principles involved in the remote sensing by passive techniques in the infrared to microwave region of the electromagnetic spectrum are discussed. Whereas the radiation below ten micron wavelength has found distinct application in many fields, the region between 0.1 to 10 cms has a decided advantage in situations where the atmospheric constituents interfere.

Part II deals with the specific problem of atmospheric interference in the 8 to 14 micron wavelength region due to water vapor and carbon dioxide. A technique for correcting radiometric measurements of surface temperatures for interference by these two constituents is suggested.

Part III deals with the potential applications of infrared and microwave radiometry to the measurement of surface temperature of natural water bodies, horizontal temperature gradients, and the heat flux across the sea-air interface. The relative advantages of infrared and microwave techniques are compared.

32. Larsen, J. A. "Ecotonal Plant Communities North of the Forest Border, Keewatin, N.W.T., Central Canada. May, 1967

Abstract: The vegetation of the tundra ecotone region which extends from the forest border at the south end of Ennadai Lake northward to Dubawnt Lake, some 150 miles distant, is characterized by floristically depauperate communities in the region immediately adjacent to the forest border and by an increasing number of typically Arctic species northward. This increase in richness of Arctic components in the vegetation appears related to the increasing prevalence northward of habitat conditions associated with Arctic air masses, since other factors such as topography, surficial geology, and soil parent material seem relatively uniform throughout the region, and since sufficient time has elapsed following the most recent major climatic change to permit species to migrate to the geographical limits of their environmental tolerance. Recent work has shown that the mean position of the Arctic frontal zone is associated with increasing values representing presence of Arctic species in the plant communities along a line northward. Thus, from the evidence presented, it appears possible to define the extent of this climatic transition zone on the basis of the structure of the plant communities comprising the vegetation of the area, although ultimate confirmation of the hypothesis may have to await more detailed climatic observations.

33. Mitchell, Val L. "An Investigation of Certain Aspects of Tree Growth Rates in Relation to Climate in the Central Canadian Boreal Forest"
July, 1967

Abstract: The Department of Meteorology of the University of Wisconsin has collected several thousand tree cores from central Canada. These cores provide the basis of this study. The core samples were surfaced by sanding and ring widths were measured using a partially automatic measuring device.

An equation describing the growth trend of a tree-ring series is derived and used to eliminate the growth trend from the ring series. After the growth trend is removed, the data is standardized to form a tree-ring index series which can be compared with appropriate climatological data.

An index of average growth of black spruce is mapped and isolines of growth are found to parallel the tree line. A theoretical tree line is defined and located.

Factor analysis is applied to tree-ring data from Canada and the western United States. The resulting set of eigenvectors show that there is more than one way in which a narrow or a wide ring is formed. The eigenvectors also show the combinations of climatic parameters that result in a narrow or a wide ring.

34. Bryson, R. A. and W. M. Wendland "Tentative Climatic Patterns for Some Late Glacial and Post Glacial Episodes in Central North America"
November, 1967

Abstract: It has been found that the annual migration limit of some airmass boundaries is very similar to the location of biotic ecotones. The superposition of meteorological and biotic boundaries suggests a technique to investigate climatic regimes of the past. If the present inter-relationships existed in the past, using the principle of uniformitarianism, i.e. the present is the key to the past, one can infer past climatic structures based on biotic information of the time in question.

Information of the late- and post-glacial time is beginning to emerge from pollen diagrams, macrofossil

deposits and faunal remains. Such evidence has been studied at tens of sites in North America. While each data site may be rather far removed from its closest neighboring site, meaningful synoptic meteorological patterns can be deduced from these data since airmass boundaries tend to be rather smooth, flowing lines, and certain features of these patterns are essentially "anchored" by geographical features.

The modal climatic patterns for three periods were constructed. The first was the late-glacial period about 13,000-10,000 years B.P. (before present). The second was a time of minor glacial advance, from 9,000-8,000 years B.P., and the third was early sub-Boreal time, about 5,000-3,500 years B.P. These particular times were chosen because ample evidence suggests that these times were significantly different from each other and different from the time both before and after the period in question.

The floral and faunal information enables one to locate seasonal limits of various frontal movements. Basic meteorological principles enable one to add areal continuity to the surface charts and construct the broad features of an upper air pattern.

The evidence available for the last 3,500 years suggests rather minor fluctuations. These are discussed in the text. This approach of paleoclimatic study requires the aid of many allied fields, and additions and corrections will undoubtedly be made to this series of tentative climatic synoptic patterns.

35. Bryson, R. A. and W. M. Wendland "Radiocarbon Isochrones of the Retreat of the Laurentide Ice Sheet" December, 1967

Abstract: A map of northern North America is presented which shows isochrones of the outer limit of the Laurentide ice sheet from about 13,000 years ago until the present. The data points are radiocarbon dates of moraines, basal peat, and lacustrine deposits which represent the dates of deglaciation. The chronology of the ice sheet shows that the ice front retreated northward from the Great Lakes to south of James Bay by about 8,000 years ago. By about 7,500 yrs. B.P., the continental ice sheet was split by an open Hudson Bay, with one center of ice over northern

Keewatin and Baffin Island, and another about 400 km south of Ungava. By 7,000 yrs. B.P., the ice over Baffin Island had separated from the mass of ice to the west. The Baffin Island ice remained after that time, and apparently is found today as the Barnes Ice Cap and the Penny Glacier.

The ice retreated faster over the Prairie Provinces than over the Labrador-Quebec area, suggesting that snowfall and/or cloud cover inhibited the retreat in the more maritime area. A glacial energy balance is presented which compares a glacial net radiation regime to that of a non-glacial time. The effect of variations in mean cloud cover and snowfall upon the ablation rate are investigated. It is suggested that cloud cover is the important determining factor for glacial net budget at lower latitudes, and that snowfall is more important at higher latitudes.

36. Wendland, W. M. and R. A. Bryson "Aerial Surveys of Hudson Bay Surface Temperature-1967" December, 1967

Abstract: Aerial surveys of the surface temperature of Hudson Bay were completed in July, August and October of 1967. An airborne infrared radiation thermometer remotely sensed the surface radiation temperature. The surface temperature patterns are presented for each survey. Certain persistant surface thermal features were found during the first two surveys. In October,,the temperature pattern was rather flat, and the large scale features mentioned above, although present, were not as well defined.

Because the ice lingers on Hudson Bay into August, it leaves its "signature" on the surface. A cold pool (presumably low salinity and therefore relatively low density) was found near the area of last ice. Due to the stratification of the upper layer of the Bay, this cold pool persists throughout most of the ice free season.

37. Ahrnsbrak, W. F. "Summertime Radiation Balance and Energy Budget of the Canadian Tundra" January, 1968

Abstract: As a step toward understanding the interrelationships between landform, vegetation, and climate of the

Canadian tundra, summertime radiation balance and energy budget data obtained during July and August, 1966, at three locations in the district of Keewatin, N.W.T., are presented. Comparisons are made between these findings and estimates from other authors' global and hemispheric radiation balance studies and also with energy budget studies of other investigators at Resolute Bay, N.W.T., and at Point Barrow, Alaska. The climate is shown to be one in which latitudinal and seasonal differences account for most of the variation. While during July the storage of heat in the soil accounts for fifteen percent of the energy budget, during the rest of the snow-free season net radiation is nearly balanced by transfer of sensible heat to the atmosphere.

38. Peterson, J. "Measurement of Atmospheric Aerosols and Infrared Radiation over Northwest India and Their Relationship"
January, 1968

Abstract: During April and May, 1966, airborne measurements were made of atmospheric aerosols and infrared radiation over northwest India up to 30,000 feet. Simultaneous observations of infrared radiation were also made by balloon-borne net economical radiometers. The instrumentation, which detected both the particle size distribution and vertical variation of the dust concentration as well as the directed infrared radiative flux, is described.

The vertical distribution of the aerosol density was measured on five separate occasions. High concentrations of approximately 700 $\mu gm\ m^{-3}$ were observed throughout the lowest several thousand feet of the atmosphere with decreasing amounts above. Three low-level size distributions were measured, all of which were similar, and in general these can be expressed by the relation $dn/dr \sim r^{-3.5}$, for sizes greater than 0.3 micron. A mineralogical analysis of the collected aerosols indicated that quartz was their major constituent.

The nocturnal radiation measurements showed several features which suggested that the infrared radiation was being influenced by the atmospheric dust. In particular, the observed upward flux was consistently greater than similar calculated values,

based on dust-free conditions, and these observed--calculated differences diverged throughout the low levels of high dust density. Observed values of radiative diabatic cooling were significantly larger than the corresponding calculated values, and the observed values were greater when the total amount of dust observed in the troposphere was greater.

Radiative transfer equations were formulated in an attempt to compare the difference between the observed and calculated upward infrared flux data to the simultaneously measured aerosol values. Based on the assumption that all the particles were composed of quartz, the Mie theory was used in conjunction with the observed aerosol size distributions and mass concentrations to calculate the wavelength dependent optical parameters of the particulates (i.e., efficiency factors, scattering albedoes and phase functions). The radiative transfer equations were developed in terms of a model in which the pertinent parameters could be varied so that their effect on the infrared radiative flux could be investigated. When the emissivity of the ground was assumed to be less than 1 and the temperature of the ground to be colder than the shelter temperature, the theoretical results of the model agreed with the observations in the low levels but were of the wrong sign at higher altitudes.

Regression analysis was then used to re-examine the relation between the observed-calculated flux differences and the atmospheric aerosols by using the radiation observations as input into a slightly modified form of the transfer equations. This study indicated that these differences were largely explained by a positive contribution from aerosol scattering. The technique of regression analysis greatly reduced the variation of the aerosol-flux difference relation. Predicted values of observed-calculated differences were near zero for low dust densities but became progressively larger at higher concentrations. Finally, an expression was presented which relates the amount of atmospheric dust to the additional radiative diabatic cooling resulting from this dust.

39. Schlesinger, R. E. "A Short Numerical Method of Calculating Heat Content of Lakes"
January, 1968

Abstract: Given a non-isothermal sounding, a lake is partitioned systematically into layers. The temperatures at their vertical midpoints are taken as representative for each layer. The hypsometric data are fitted to a simple power profile such that the actual and approximating basins have equal volumes. By the use of these simple functions, the integral which defines heat content is easily evaluated in cosed form.

The two-layer method is tested on 46 open-season soundings for nine temperate North American lakes. The two-layer heat content values are compared to those obtained by the method of Bryson and Dutton (1960) in their analysis of Lake Mendota. The results suggest that the two-layer heat content values are not significantly different from the Bryson-Dutton values except for soundings having the steepest temperature gradient near the surface. An effective scheme is devised to correct for large differences. The shapes of the areas bounded by a schematic summer sounding and the two-layer curve are considered.

The method lends itself readily to FORTRAN computor programming, and no special subprograms are needed. Although the method as presented requires complete soundings, it can be applied with slight changes to lakes with thermoclines when only the hypsometric data, surface temperature, bottom temperature and thermocline depth are known.

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