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Freeze-thaw phenomenon as a climatological parameter

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FREEZE-THAW PHENOMENON AS A CLIMATOLOGICAL PARAMETER

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CHAPTER I

THE CONCEPT OF FREEZE-THAW AS AN INDEX TO CLIMATE

The concept of climate as one of the principal controls in the formation and content of the natural landscape has become almost an axiom among geographers and others in closely related fields. This is particularly true with regard to the major distributional features of the natural vegetation. As a result, there have been a number of attempts to relate climate, per se, and vegetation patterns. In fact, the merits of most new climatic classifications have been judged according to how well vegetation patterns are reflected by the delineated climatic provinces. This would appear to be a valid criterion since the bases for the climatic classifications are usually the limits, in terms of temperature and precipitation, considered critical to vegetation. Exception to this may be made for general classifications from the related field of meteorology. But these have generally proven too cumbersome for similar application to the problems of the landscape.

Of the many classifications proposed, Koppen's is outstanding and is commonly used among geographers. In one way or another, it has found its way into many textbooks and the symbols have become a descriptive climatic shorthand. The broad base for this classification is de Candolle's classification of vegetation according to its requirements or tolerance of temperature and drought. Upon this Koppen adopted Penck's distinctions made between the nival and humid climates and between the humid and the arid climates. However, Koppen was never completely satisfied with his temperature-precipitation relationships and he revised these several times. The classification has the merit of flexibility in its use of temperature and precipitation data. Incorporated were temperatures of the warmest month, of the coldest month, and the number of months above a particular level when these conditions were considered significant. In addition, the relative importance of temperature in humid areas and of precipitation in dry areas was also considered. This was a rather new application when the classification was in its initial stage of development. The popularity of the Koppen system is well deserved and as a teaching tool, it is easily adaptable.

Another system gaining in popularity was proposed by Thornthwaite (35) originally in 1931 and later revised by him in 1948. In his classification Thornthwaite reverses the usual approach and considers the moisture cycle to be of principal importance, thereby relegating temperature to a secondary role. The broad base is potential evaporation which does not represent actual transfer of water to the atmosphere, but rather the transfer that would be possible under ideal conditions of soil moisture and vegetation cover. In the 1948 study, vegetation is treated as a physical mechanism by means of which water is transferred from the soil to the atmosphere. The concept of potential evapotranspiration is undoubtedly valid, but the stumbling block becomes the adequate representative measure of such a factor. However, Thornthwaite's approach has the merit of being interesting and it is certainly a step forward. But based on the present available data, the climatic regions are open to some degree of suspect.

If the problem of climate in its relationship to the organic and inorganic features of the landscape is to be taken seriously, then both Koppen's and Thornthwaite's systems fall short of the ideal. Even the general field of Ecology, a science vitally concerned with the relationship of vegetation and animal worlds to their natural environment, has not apparently discovered significant insight into the overall problem of climate and the natural landscape. Despite the many excellent works of a detailed nature, conclusions are valid only up to a point. Then, there usually appears a hedge for more specific knowledge of the physiological requirements and of the climate in order to determine whether the differences noted are sufficient to be attributed to climatic control.

The principal omission in the usual approach to temperature and precipitation is the dearth of natural breaking points in the data as processed. It would appear axiomatic that in order to propose a rational quantitative approach to climate, a definite and distinctive break point must be discovered in the data. It is upon the occurrence of such a breaking point in terms of temperature that the phenomenon of alternate freezing and thawing is considered for a systematic investigation as to its possible significance as a climatic parameter. Previous work has usually limited discussions to alternating freezes and thaws in the higher elevations or latitudes where the results on the landscape are most evident. Several systematic studies have been made on the areal distribution of the frequency of the freeze-thaw cycle. But by using the usual approach to climatic distributions little beyond the gross pattern is revealed. The possible significance of the physical process in terms of climate has seemingly been overlooked.

In several respects, the freeze-thaw cycle might answer a number of objections to the usual concept of a climatic parameter. First, a finite physical process is involved. Second, the possibility of its occurrence is dependent upon fluctuations through a definite, measurable temperature threshold. Third, there are relatively large amounts of heat involved in the changes from the liquid to the solid state or the reverse. Fourth, tremendous mechanical force may be available during these changes of state. Fifth, there is the physiological importance of the availability or non-availability of liquid water. Then, too, the process occurs or is possible under natural conditions due to the integration of the individual climatic elements and as such becomes a measure or index to the climatic condition then prevailing. The distinct advantage is the measuring of an integrated total, as against the attempt at the integration itself from lists giving the scalar values of the individual parts. By using an integrated level of climate, there should be an improved possibility of casting some light on the natural laws controlling the physical environment of the earth especially in that area of interest shared by both the climatologist and the geographer.

From both theoretical and practical aspects, it would appear that freeze-thaw activity or conditions favorable for its occurrence may be significant in terms of climate and that, perhaps, the activity may be reflected to a recognizable level in the natural landscape. The primary objective of this study is the systematic investigation of the areal occurrence of the process of freeze-thaw, or of the temperature conditions favorable for occurrence, in terms of its possible climatic significance. The secondary objective is to ascertain whether this process leaves a recognizable imprint on the landscape in those areas where it may occur. The approach to the problem uses the monthly activity in terms of: first, frequency of occurrence; second, whether the fluctuation through the temperature threshold is to be considered as a freeze or as a thaw; third, duration in days of each freeze or thaw; and fourth, the average severity of the freezes or thaws during the month. If upon this data, an orderly and logical sequence in the regionalization of the freeze-thaw activity is possible, then the premise of its climatic significance can be assumed as valid. If corroborative support can be found with distribution patterns of such features as precipitation, vegetation, soils, etc., then the premise can be considered as proven.

The use of the phenomenon of freeze-thaw in developing a climatic classification has been considered but, here, this thought furnishes only a background to the study or at most a sought after goal for future work. It would appear that a degree of sophistication in the development of a rational classification of climate must necessarily reflect a corresponding understanding of the subject. In climatology this could be considered a significant step forward. However, the scope of this investigation is limited to proposing a premise and developing that premise to the point where its validity can be ascertained to a reasonable degree.

CHAPTER II

FREEZE-THAW AS A PARAMETER

The Phenomenon and Scope of Freeze-Thaw

Freeze-thaw phenomenon has a uniqueness seldom found in nature; that is, acuity in its discrete changes of phase. The contributing factor is the exchange of heat during the process. Approximately 80 calories are released by 1 cc or gm of water on its transformation into ice and, of course, 80 calories are needed to reverse the process. Because of these discrete changes being dependent upon a relatively fixed temperature level, the phenomenon can be considered in terms of a parameter. Unlike the usual meteorological elements which are measured on relative scales having no relation with each other (i.e., degrees, inches, direction, mph, per cent), freeze-thaw represents a finite physical process and is measurable in terms of frequency, severity, duration and time of year of its occurrence. This data is readily obtainable for an extensive geographic coverage from the usual published records giving the daily maximum and minimum temperatures for the reporting stations.

The freeze-thaw process may be one of the more powerful and consistent tools operating in nature. Mechanically, extraordinary pressures even to the extent of one or two thousand atmospheres could be involved. These pressures are affected by the density differential of water between its liquid and solid states. At 32° F or 0° C, the density of water is only slightly less than 1.000 gm/cc, while on becoming ice at the same temperature, the density lowers to 0.917 gm/cc, or, in other words, on becoming frozen the water now occupies about 11 per cent more volume. Considering that it takes over 300 atmospheres to lower the freezing point to 27.5° Fahrenheit; over 600 atmospheres to lower it to 23.0° F; over 1000 to 14.0° F; and over 2000 atmospheres to lower the freezing point to -4.0° F, it is readily apparent that the confining walls of any trapped water must be exceptionally rigid or suffer deformation. Permanent deformation would occur unless restraining walls have sufficient elasticity to accommodate the expanded volume of the ice and yet return to their original state on the reversion of the ice back to a liquid.

The landscape has several features directly attributable to the mechanical phenomenon of alternating freezes and thaws, though these features are, in general, limited to those areas in the higher elevations and latitudes where erosion due to running water has been and is relatively minor. Flint (9) describes the development of small cirques by the process of nivation, a collective term for the effects of freeze-thaw in the higher elevations. These cirques may be formed at the level of perennial snowbanks where the melt water flows into the crevices and freezes at night thereby expanding and wedging out small rock fragments which then move down slope. The resultant form is a semicircular depression with a flattened floor and steep sides. Such cirques are not in themselves evidence of glaciation. However, the wedging action is in evidence most everywhere, when, in the presence of water, the temperature fluctuates through the freezing point. The action is possible under conditions of fluctuating pressure such as may exist under a glacier moving over an uneven floor. The release of the pressure might well lead to the freezing of the residual melt water in the crevices and the wedging or plucking action on the lee of any obstacle.

Pearsall (26) attributes the characteristic mountain detritus in Great Britain to disintegration of the native rock by frost action. The detritus sometimes accumulates to a depth of several feet. The frequent freezing and thawing has the effect of mixing the upper layers and, in particular, that of floating rocks to the surface. This particular action provided the prime supply of material for many scenic stone walls in New England. Pearsall also attributes the varied flora of the mountain grasslands to the mixing action within the soil by the freeze-thaw cycle. Resulting soil instability apparently inhibits the establishment of a stable plant community. Benninghoff (5) also found this to be true among the plant communities in the arctic. He was even able to associate distinct plant communities with particular types of frost features. But then, the plants commonly modified or changed the frost activity in the soil to such an extent that they frequently destroyed the very micro-environmental conditions that favored their establishment and growth. Instability in the soil is also promoted by the process of solifluction or the slippage of the water-saturated layer of soil over the still frozen layer beneath. According to Pearsall (26) and Penck (27) this process is particularly active in the spring when rain water at this time combines with melted water held within the upper layers of the soil to the point of saturation. Under such conditions and especially with the accompanying expansion and contraction of freeze-thaw, the upper layers are subject to slippage on even the gentlest of slopes. Pearsall also attributes the formation of stone stripes and polygons in mountain and high latitude landscapes to the freeze-thaw phenomenon. The actual sorting process is not completely understood, although the finer material is found between the stripes and within the polygons. Troll (38) describes these stripes and polygons as they are found in many elevated locations of the world.

While the mechanical work of the freeze-thaw activity appears most prominently in the higher elevations and latitudes, the process would appear to be an important parameter in the formation of landscapes in other areas as well. In such areas the direct mechanical effects may well be obscured or obliterated by wind and water erosion. Nevertheless, there is an important physiological effect - the availability or nonavailability of water to sustain growth and also the relatively low temperature at which the process takes place. Among the various vegetative species there are many levels of tolerance to the frequency, duration, and severity of the process. Over a period of time this must have contributed to the natural plant selection within a given area. Whether the imprint is sufficient to show as a corroborative feature is one aspect within the overall problem.

In soils freeze-thaw acts as both an accelerator and retarder in their development. It accelerates the disintegration of the parent material in the upper layers through exaggerating the expansion and contraction cycle within the pores and crevices while, on the other hand, it inhibits bacterial and chemical processes during the frozen condition of the soil. Whether the impact is sufficient to contribute to the differentiation within a material subject to other and more active processes is a moot question. But on considering that the measure of freeze-thaw activity may also be an index to the climate, it would appear worth while to investigate soil distributions as another possible corroborative feature.

Several of man's activities, too, reflect the impact of the freeze-thaw activity. This is especially apparent in his agricultural and constructional endeavors. There are continuing efforts to extend crops into marginal growing areas by either shortening the growth period needed to reach maturity or by breeding more frost-resistant varieties. Efforts extend even to the use of costly frost preventive measures to combat the occasional severe frost which can create such havoc among certain specialized crops. In the constructional field most building codes specify a minimum depth for foundations, thereby principally reflecting the severity of the cumulative frost action within the particular area. Concrete, a common constructional material, has long had the weakness of spalling under the effects of alternate freezes and thaws. Research has overcome much of the problem although it is still a factor in areas where salt is used to remove snow and ice from the roads. Alternating freezes and thaws are the salient factors in the development of the apparently inevitable spring potholes occurring in many roads. The activity opens up crevices in the pavement by exaggerating the expansion and contraction cycles thereby permitting water seepage to the foundation. Under heavy traffic the foundation will give way resulting in an uneven pavement or in the expected spring pothole.

The process of freeze-thaw or the favorable conditions for its occurrence exists over large geographic areas of the world. In several respects, the world-wide freeze-thaw pattern can be anticipated in terms of frequency, severity and duration from what is known of the temperature regimes in generalized areas. Using the tropics as a reference point, an almost daily freeze-thaw cycle could be expected in the higher mountainous reaches such as the Andes. In fact, Troll (37) found in processing temperature records of a Harvard expedition into the southern Peruvian Andes that the elevation at which the temperature would begin to fluctuate through the freezing point started at about 10,000 feet. From this level to around 13,000 feet the number of days experiencing the freeze-thaw cycle increased rapidly to about 340 per year. Around 16,000 feet, days when the temperature did not rise above the freezing point would occur, and at about 19,000 feet this situation could be expected for practically every day of the year. Thus from a maximum frequency in the highlands of the tropics there would be at these elevations a gradual decrease poleward approaching the lower limit of close to zero in the arctic and antarctic wastes. On the other hand, the zero frequency expected in the lowland tropics would gradually increase on moving poleward, reaching a maximum in the midlatitudes and then decreasing in number on continuing toward the poles. Superimposed upon this pattern would be the effects of continentality and maritimity, where in the former case temperatures would be expected to plummet rapidly through the freezing point in the fall and correspondingly rise rapidly in the spring. Maritime conditions would be expected to modify the frequency of occurrence while in areas subject to both influences, such as east coasts, the frequency could rise radically thereby reflecting the oscillation between the two factors. Valleys and other sheltered areas would show modifications from the general pattern. Obviously, a strong topographic control is reflected in the freeze-thaw pattern.

Considered as an entity, freeze-thaw phenomenon appears to warrant a place as an important climatological parameter. The proposed systematic investigation of the phenomenon on an areal basis and its relation with established environmental factors is definitely a problem in physical geography. It is fundamental within this field in two respects: first, there is the consideration of a physical process which could occur frequently in nature but appears not to have been given its true recognition; and, second, it is a systematic study investigating the areal distribution of the process and its possible associations. On the other hand, the "cause-effect" relationship on a large scale is definitely neither expected nor anticipated. Support for the premise will be based mainly upon an orderly sequence developing within the overall distribution pattern of the freeze-thaw phenomenon and, secondly, upon the level of association over extensive areas with recognized factors, such as precipitation, temperature, vegetation, or soils. If the pattern develops logically with natural break points in the data and there is a significant association developing with other environmental factors, then the premise can be considered substantiated.

The Objectives of the Study

Previous systematic studies concerning the phenomenon of freeze-thaw have been principally concerned with the yearly frequency of the cycles. Alpert in contributing to a Structural Clay Products Institute report (33) computed the frequency for twenty-four major cities within the United States using the temperature threshold of 32° F. A major contribution to the field of geography is made by Russell (29) who concerned himself more with areal differences than with point differences. However, the approach utilized by this investigation and those used in previous studies differ significantly in at least three ways: first, what is involved by the phenomenon of freeze-thaw; second, the amount of applicable information inherent in the basic temperature data; and third, the cartographic presentation of the data.

In the constructional field the concern with freeze-thaw has been in terms of mechanical stresses to be sustained by the resulting structure whether it be a roadbed or, in the case of Alpert's study, the clay veneer applied to a building. Russell implied the effects of both the mechanical and physiological stresses by the use of such terms as "effective" for freeze-thaw at the air-ground interface, and "killing frost" with respect to vegetation. This study, however, is concerned with the phenomenon of freeze-thaw as a finite physical process which by virtue of its dependence upon a definite and in many areas a frequently occurring temperature threshold may be to some degree a measure or index to climate and because of the mechanical and physiological factors involved may leave a recognizable imprint upon the natural landscape. Thus, thereby establishing a determinable link between climate and the natural landscape.

The second principal difference is in what constitutes a significant level of information. Previous studies were primarily interested in the yearly number of cycles, whereas in this study natural breaking points in the freeze-thaw data are being sought. To accomplish this objective, something more detailed than frequencies is needed. Data are processed on a monthly basis to provide duration, severity, and frequency of freeze-thaw and to determine whether the activity during the months is to be identified as a series of freezes or thaws. Furthermore, whether freezes or thaws are limited to one day, two days, or whether durations of three, four, or more days occur are significant. The relative severity of the activity (that is, the minimum temperatures associated with freezes and the maximums with thaws) also provides a significant index. What was sought was a relative measure of the freeze-thaw activity which permits discrete comparisons to be made between reporting stations.

The third difference is in the cartographic presentation of the freeze-thaw data. Alpert's purpose was served by a table giving the yearly frequency for individual cities. Russell also uses tables for discussing point to point differences, but the main body of data is presented in map form by using isorithms. Russell was confronted with a spread running from 0 to 188 cycles per year, which he partially solves by using a progressive series of fractional parts of a year. He begins the series with ½ because the highest frequency approximates half the number of days in the year. The next fraction in the series is ¼ and so forth along the progression. The result was not considered completely satisfactory because of: (1) the very close spacing of the isorithms in the west coastal area and (2) the result by chance of the intervals within the progressive series. Because of the latter, the Mississippi drainage basin was undifferentiated; similarly, the same undifferentiation prevailed in the plateau and mountain region of the West. This he resolves by incorporating an extra isorithm in each of these areas. With respect to the resulting map presentation, Russell makes a rather revealing statement, "The climate records themselves permit no other course but in order to . . . . ." (29, p. 130). His reflection, of course, is upon the limitations of his cartographic presentation rather than upon his data or the climatic records that he used. Nevertheless, Russell's work has a significant application to this study in that it proves that arbitrary divisions of freeze-thaw activity are in themselves meaningless. The problem of visual presentation of climatic data is partially explored by Landsberg (16). One suggestion is the possible use of diagrams for some of the elements. This method is employed in this study. All the variable data over the year are incorporated into one diagram for each station. Included on a monthly basis are the factors of frequency, duration, severity, and their determination as freezes or thaws. The diagrams have greatly aided the interpretation of the data with respect to differentiation from station to station.

CHAPTER III

ESTABLISHMENT OF THE FREEZE-THAW THRESHOLD

The Temparature Zone for Freeze-Thaw

The sources for the maximum and minimum temperatures used in this study are the Monthly Record issued by the Meteorological Division, Department of Transport, Canada and the Climatological Data published by the United States Weather Bureau, Washington, D.C. As a whole, the geographic coverage is very good. Cooperative observers are in many remote places and their records fill an otherwise blank area. For these reasons their records are considered the more suitable for a study of this type. Agricultural stations, too, are often located in sparsely settled areas and their records are also very useful. However, most meteorological networks are comprised of airport and city stations and of the two, airport stations are used when possible since these are a better approximation of the natural environment.

As for the number of years of record necessary to establish a stable distribution, Russell (29) found that for many stations a three year record was sufficient to arrive at a stable yearly freeze-thaw frequency. Even for those stations with a history of erratic temperature regimes, he found little change in the cumulative averages when data beyond that of the sixth year was employed. This length of record is far less than that advocated by Landsberg and

Jacobs (18) for establishing a stable frequency distribution for temperature. For extratropical regions they recommend 10 years of data for island stations, 15 years for stations near the shore, 15 years for plains, and 25 years for mountain locations. For tropical regions the number of years of data recommended extends from 8 for island stations to 15 for stations in the mountains. It would then appear that the freeze-thaw process is a more conservative factor than the temperature element from which it is derived. The limiting factor in this study is not the stableness of the yearly frequency, but the variability between freezes and thaws occurring during a particular month. At a number of stations the temperature regime for a particular month has sufficient range over the years so that for some years the fluctuations through the freeze-thaw zone are considered as thaws and in other years as freezes. This variability is generally a distinctive feature in the freeze-thaw pattern at the station where it occurs. The variability is usually well stabilized by processing seven years of data and the work of processing additional data does not seem commensurate with the slight additional level of difinitiveness. For most stations, therefore, seven years of record were processed for the needed freeze-thaw data. A few stations in the more remote reaches of Canada with only four or five years of data are used where desirable geographic coverage was needed.

While it is relatively easy to measure temperatures or the absorption and dissipation of heat in the laboratory, the natural environment does not provide such precise materials, controls, or results. It is possible to supercool pure water to -70° C; or impurities may depress the freezing point by one or two degrees. Pressure is capable of doing the same or much more and this need not be an external force but may be applied solely by surface tension if a droplet is minute. The heat regime in nature is also a variable. Meteorological data collected and processed as climatic records for a particular site and level may differ by several degrees from an area only a hundred or more feet away. Furthermore, the actual process of freezing or thawing is not instantaneous but requires a factor of time as the latent heat is either being dissipated or added. Time in this case is a variable dependent upon the temperature differential between the air and the freezing or melting point of the water. A differential of 1 or 2 degrees over a longer period of time will be equally effective as a larger differential over a relatively shorter period. Considering these factors, a certain degree of subjectiveness is inevitable in establishing temperature levels for the occurrence of a freeze or a thaw in the natural environment and especially when the term "effective" is implied if not used.

The largest variable involved is that of the actual temperature regimes in the natural environment. Temperature data on an extensive areal basis is available only from the climatological records. These temperatures are obtained within a well ventilated shelter which is exposed to the free movement of the air. On the other hand, within the quite limited vertical zone encompassed by the natural environment, it is frequently not the question of the free-air temperatures but that of air restrained to some extent by vegetation, terrain, or both. How closely shelter temperatures represent temperature regimes of air under restraint by the landscape is not completely understood. Nevertheless, for the limited objectives of this investigation the representativeness of shelter temperatures poses no serious problem. It is quite likely that the problem of representativeness of temperature data would place a limit on the degree to which the study of freeze-thaw may be pursued and in what detail.

Considering the three variables involved: first, the slight depression in the freezing or melting level due to possible impurities in water; second, the marked variation in temperature regimes near the ground over short distances; and third, time interval for the process to take place; the temperature levels of 34° F and 28° F were selected. When the temperature drops from 34° F or above to 28° F or below, temperature conditions are considered conducive to the freezing of water in the natural environment. Conversely, when the temperature rises from 28° F or below to 34° F or above, temperature conditions are conducive to the melting of ice or snow. From personal experience in measuring temperature differences over short distances within a relatively homogeneous terrain possessing diverse vegetative cover, the author (41) selected the upper limit of 34° F. The lower limit of 28° F appears to be rather critical in that a level of 2° lower than the selected value materially affects the freeze-thaw patterns for certain stations particularly those experiencing mild climates such as the West Coast and Gulf States. It must be kept in mind that this study is an analysis of the relative differences of freeze-thaw activity from station to station over the rather extensive area of Canada and the United States. Thus, this study is concerned more with attaining a reasonable and acceptable base to make such comparisons. The temperature levels of 34° F and 28° F satisfy best the broad areal requirements and yet appear stringent enough to warrant the implication of "effective".

Freeze-Thaw Data and Their Graphic Representation

From the daily maximum and minimum readings at a station, the following items of information are available: first, frequency, that is, the actual number of occurrences per month; second, duration in days for each freeze or thaw; third, the severity of the freezes or thaws; and fourth, the nature of the temperature cycles; are they freezes or thaws? In processing the temperature data, the initial step was a check on the monthly averages of the maximums and the minimums to determine whether the fluctuations were to be considered in terms of freezes or thaws. When the average monthly minimum temperature was 34° F or above then any temperature fluctuation of 28° F or below would be considered as a freeze. Similarly, when the average monthly maximum temperature was 28° F or below a temperature fluctuation to 34° F or above would be treated as a thaw. Usually, however, this was determined by the relative differences between the average monthly maximum temperature and 34° F on the one hand and the average monthly minimum temperature from 28° F on the other. When the former were greater, the fluctuations would be considered as a series of freezes; when the latter were greater they would be considered as a series of thaws. When it was not immediately apparent what was the identity of the series, the sum of the individual departures of the maximums above 34° F was compared with the sum of the individual departures of the minimums below 28° F. Again, if the former were the larger, then the fluctuations would be considered as a series of freezes and if the latter were the larger, then as a series of thaws. The durations of the freezes and thaws were determined by the number of days during which the temperature remained at or below 28°F and at or above 34° F as the case may be. The severity of the freeze or thaw was determined by the departure of the extreme temperature below 28° F or above 34° F, again as the case may be. The monthly average was obtained by dividing the sum of the departures by the appropriate number of days when either freezes or thaws occurred. Figure I shows how this information may be shown by graphic means.

The base line in the diagram extends from July through December (D), January (J), and June. The purpose of this arrangement is to effect continuity in the monthly presentation of the data since in the more northern areas the activity of freeze-thaw is continuous

Figure I is based upon data for Cranbrook, B.C., a station located in a rather narrow but high valley enclosed by mountains. The high yearly frequency of 103 freeze-thaw cycles is consistent with what would be expected from its location and elevation of 3013'. The initiation of the freeze-thaw process in the fall is light with only two freezes being expected in September when the temperature would dip about 2 degrees below the lower limit of 28° F and rise again the following day to 34° F or above. In October the number of freezes increases to about eleven, still probably an overnight dip and only slightly more severe, with the minimums now reading around 25° F. November shows the occurrence of both freezes and thaws. By estimating the length of the column below the line to the total length of the column, an approximation can be established to the effect that in one year out of three the general temperature regime will be above the critical zone and, therefore, the activity will be considered as a series of freezes. Conversely, the other two years will be treated as a series of thaws. In either case, twelve cycles of one day duration can be expected, two cycles of two days duration, and one cycle of three days duration. The average severity will be in both cases about 6 degrees from the temperature level of 34° F for the thaws and 28° F for the freezes. During December, January, and February thaws are fairly frequent although during the colder months the maximums may reach only the 37 or 38 degree mark. March is similar to November in that in one year out of three the activity will be considered in terms of freezes while during the other two years in terms of thaws. April shows a rather high (17) frequency of freezes, though these are limited to one day duration. The activity extends into June with about four freezes to be expected. The station has only the months of June, July, and August in which the temperature will remain above the lowest critical level.

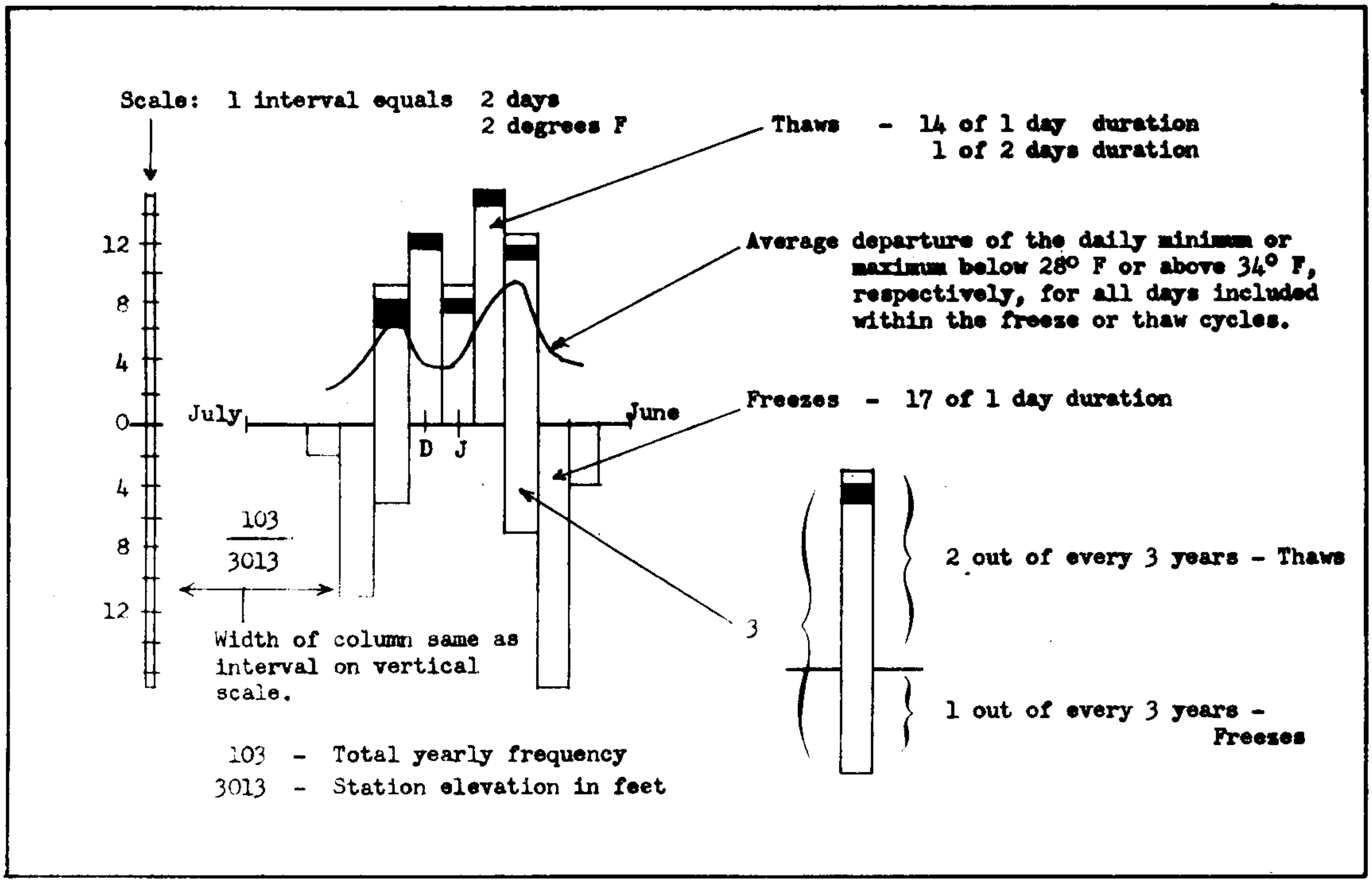


Figure I - The Freeze - Thaw Diagram

from fall through spring. Differentiation between freezes and thaws is obtained by plotting the frequency of the thaws above the base line and of the freezes below this line. The monthly frequency is shown by the length of the appropriate column. In some cases both freezes and thaws are shown for the same month. In some ways, this becomes a visual indicator of the temperature variability inherent in the climate. For example, in Figure I, March and November show this variability. In this case, the position of the bars simply means that the average temperature during these months is close to the critical zone of $34^{\circ} - 28^{\circ}$ F; for some years the average will be above and some years the monthly average will be below. In terms of freeze-thaw these months are excellent indicators of a transition period. Durations of freeze or thaw cycles are depicted within the monthly column and are commensurate with the lengths of the divisions. The first clear space from the base line is an indicator for cycles completed within 24 hours; the first solid bar for durations of two days extent; the following clear space for three day periods and the second bar for four day periods. Longer durations are experienced but these durations are averaged out by the processing. The relative intensity of freezes or thaws in degrees is shown above the base line by a curve which is more or less continuous. The upper of the two figures plotted with the station model is the average number of the freeze-thaw cycles for the year and the lower number is the elevation of the station in feet.

Data presented in the diagrammatic form of Figure I are compact and are more readily assimilated for comparison purposes involving a large number of stations than the same data presented on individual charts and tables. Interpretation to a certain extent remains subjective. This is not objectionable for the diagram contains practically all of the pertinent freeze-thaw data so that the basis for the subjective selection is in evidence.

Testing the Criteria and Presentation of the Freeze-Thaw Data

There are, actually, three premises which should be subjected to scrutiny; the principal premise being, of course, the logical sequence to the changes in the respective freeze-thaw patterns over a large geographic area. Then, there are the supporting ones of the choice of 34° F and 28° F as the critical temperature levels for determining whether a freeze or thaw could occur and of the effectiveness of the diagrammatic presentation in showing the freeze-thaw patterns. For the initial testing of the three premises, temperature records of stations within a geographic area of diverse topography and where a relatively high freeze-thaw activity could be expected are used. The area selected extends in a belt across southern Canada and the northern United States and stretches from the Pacific to the Atlantic Ocean. The 28 stations are considered a sufficient sampling to be representative of the Pacific maritime conditions, the western mountain regions, the Great Plains, the Great Lakes area, the eastern highlands, and the eastern maritime exposures. The temperature data for the 28 stations were processed using three different though overlapping temperature zones. These are: as proposed for this study, 34° F and 28° F; as used by Russell, 32° F and 28° F; and the zone of 32° F and 26° F. The latter figure is frequently considered critical to many fruit trees and vegetables. As suspected, and as evidenced by Figure II, the resulting freeze-thaw patterns are essentially very much alike. However, what differentiation exists is clearly brought out by the diagrammatic method.

Although data for all 28 stations were worked up and plotted (See Figure III, p. 32), diagrams for four selected stations are sufficient to show the major differences existing among the three freeze-thaw temperature zones (Figure II). Stations selected are: Cranbrook, B.C., as representative of the western mountains; Bismark, N.D., a Great Plains station; London, Ont., to show the influence of the Great Lakes; and Yarmouth, N.S., for the eastern maritime conditions. In terms of the total number of freeze-thaw cycles for the year there is little difference in the use of 34° F or of 32° F as the upper limit, but there is a significant difference between the use of 28° F and 26° F for the lower limit. Where the difference between 34° F and 32° F does appear noticeable is in the reduction of the thaw periods. The four day thaw is eliminated during January and February at Yarmouth, during December at London and during March at Bismark. Furthermore, there is usually some adjustment in the number of two and three day thaws. During January and February Yarmouth can now expect two three day thaws instead of one but only two two-day thaws instead of three. But in comparing one station to

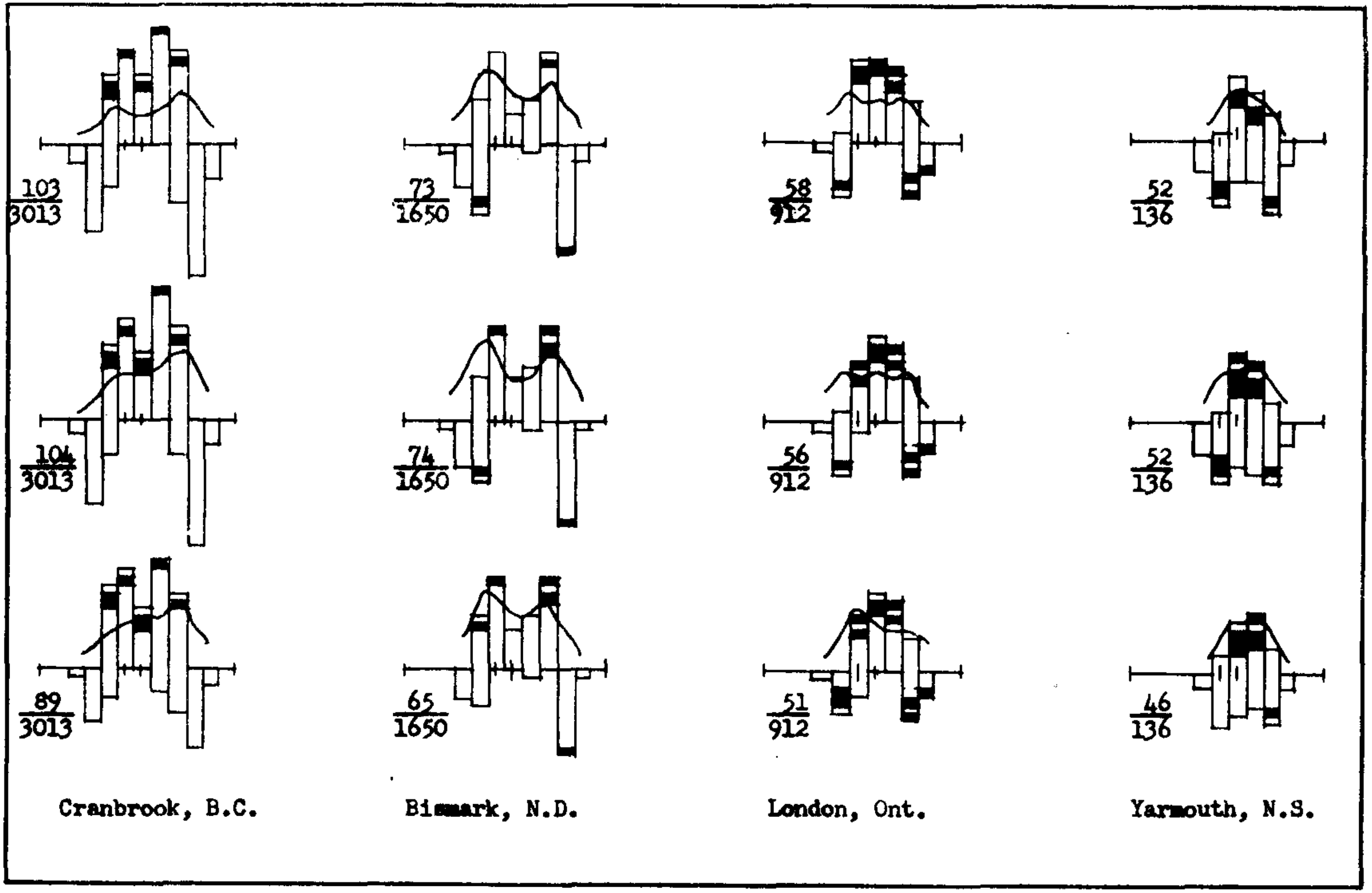


Figure II - Comparative freeze-thaw diagrams determined by using temperature levels of 34° - 28° F (top); 32° - 28° F (center); and 32° - 26° F (bottom).

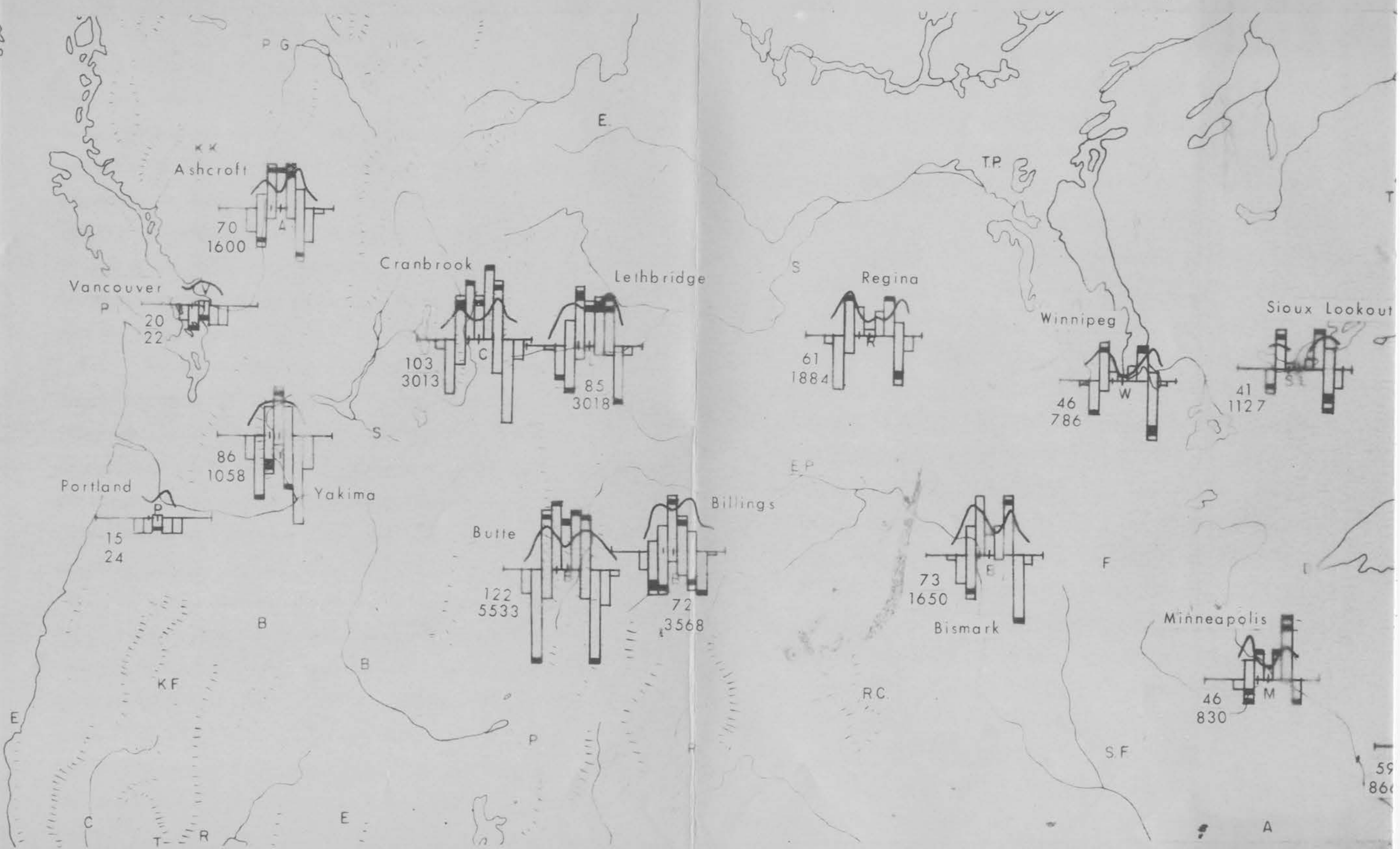
another while using the same temperature limits, the differences become rather immaterial.

The difference between 28° F and 26° F as a lower limit is noticeable at each station with the reduction in the yearly total being principally due to this change. Such a change at Cranbrook shows very clearly. Only at Bismark does the use of 26° F as the lower limit affect the overall pattern. This occurs during the month of November when thaws instead of occurring about two out of every five years, now occur about three out of every five years. Also, the use of 26° F as the lower limit could well obscure the freeze-thaw activity in west coastal areas where the principal temperature influence is the long fetch over relatively warm ocean water. And, too, the use of this lower limit might well obscure some of the activity in the more southern areas. On the other hand, the difference between 34° F and 32° F does not appear significant to the general pattern. Russell's criteria could have been used in this study. However, personal experience in measuring temperature differences over relatively short horizontal distances indicates the preference for 34° F as the upper limit and in agreement with Russell, 28° F as the lower limit.

Figure II also substantiates the premise of the effectiveness of diagrammatic presentation for station data. Certainly, the differences between stations are readily apparent as are the similarities when they exist. This is easily tested by making comparisons between the three diagrams given for each of the four stations. Consider also, the numerous items of information incorporated within the diagram and the ease with which one diagram can be compared with another in contrast to the obvious difficulty of making such comparisons from tabulated data. It becomes readily apparent that for the purposes of this study the use of diagrams is the more satisfactory method.

Among the sampling (See Figure III) the most marked contrast occurs between the Pacific maritime and the western mountain areas. On the west coast Vancouver, B.C. and Portland, Ore. show a yearly frequency of twenty and fifteen cycles, respectively, occurring during the months of November through March. Temperature fluctuations through the critical zone are considered principally as freezes but about once in every five years, general temperatures during January are sufficiently low for such temperature fluctuations to be regarded as thaws.

In marked contrast to Pacific stations, the western mountain stations represented by Cranbrook, B.C. and Butte, Mont., have a relatively high annual freeze-thaw frequency. The initial onset for the year begins in September and continues with increasing tempo through October. November is a transition month where in two out of every three years, temperatures are low and the movement of the temperature through the zone is looked upon as a thaw, but for the third year as a freeze. December, January, and February are months for thaws. Most thaws are of one day duration, but thaws lasting into the following day and sometimes for three days duration do occur about once every



P G
E.
K K
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1600
Vancouver
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20
22
Cranbrook
103
3013
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Lethbridge
85
3018
S
86
1058
Yakima
Portland
15
24
Butte
122
5533
Billings
72
3568
B
KF
E
C
T
R
E
P
B
S
Regina
61
1884
R
T.P.
Winnipeg
46
786
W
Sioux Lookout
41
1127
E.P.
73
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Bismark
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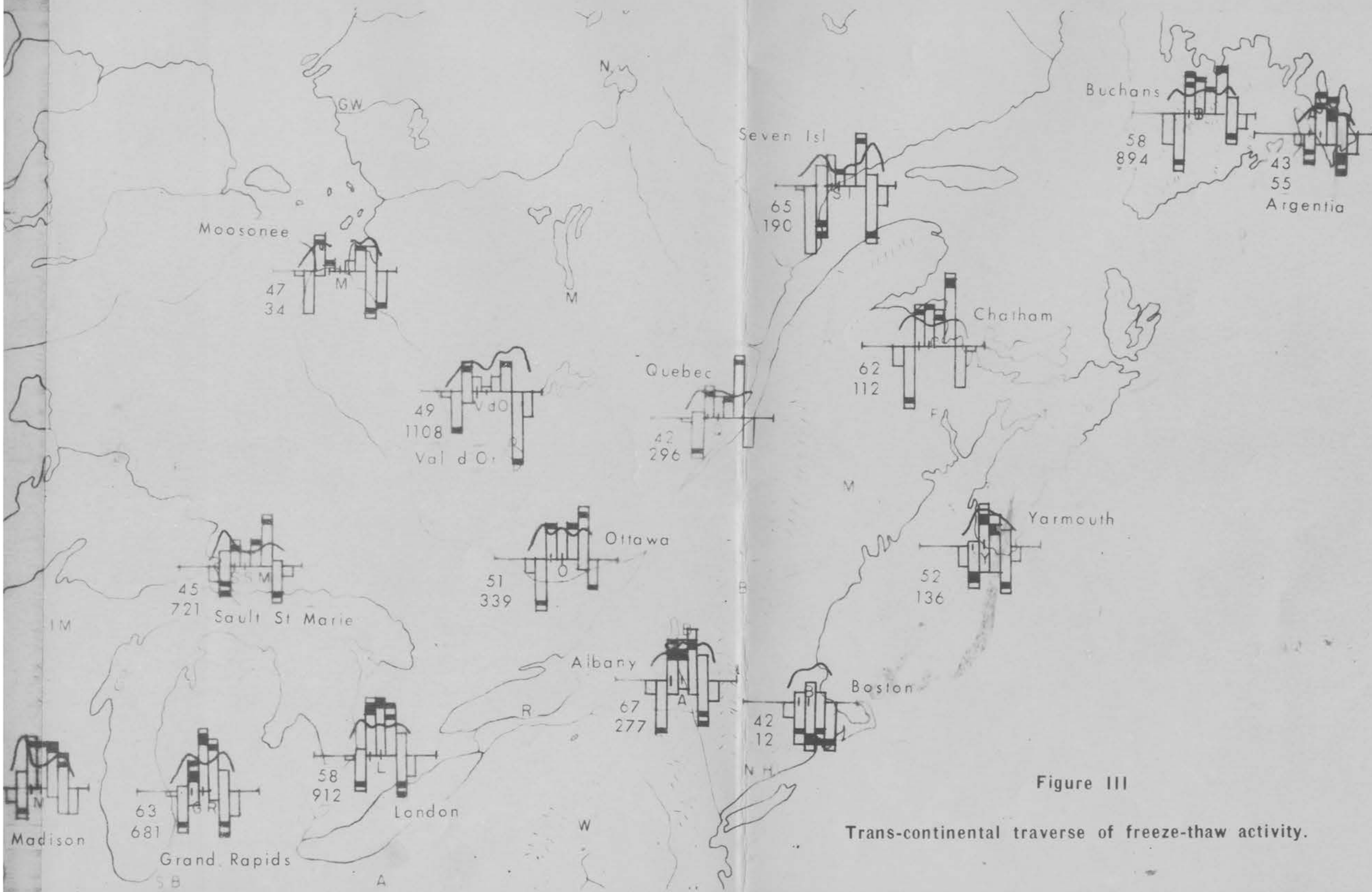

Figure III

Trans-continental traverse of freeze-thaw activity.

month. March is another transition month where about one in every three years spring arrives rather early. April shows frequent freezes and there are a few in May. At Butte, a light freeze is to be expected even in June. Both stations show a long transition period in the fall and also in the spring. Within the lee of the mountains, the freeze-thaw frequency can rise rapidly. This is shown by Ashcroft, B.C. and by Yakima, Wash. with a yearly frequency of seventy and eighty-six, respectively. The freeze-thaw patterns for these two stations are much more reflective of the mountains than the near-by ocean.

To the east there is a more moderate gradation as shown best by the Canadian stations of Lethbridge, Regina, Winnipeg, and Sioux Lookout, in that order. The fall transition period becomes progressively shorter until at Sioux Lookout it becomes quite sharp. The winter pattern also changes radically from rather frequent thaws in the mountains to much fewer at Regina and still less at Winnipeg and Sioux Lookout. In fact, Winnipeg can expect only about six thaws during the months of December, January, and February and Sioux Lookout but about three with none occurring during January. The spring transition period becomes shorter than for the mountain stations but remains practically the same for the four stations east of the mountains. With slight change, Billings, Mont., and Bismark, N.D., also follow this pattern of changes with the principal differences appearing in the severity of the winter. Every month at Billings is variable in terms of freezes and thaws and this may well indicate the peculiarities of its own particular exposure. The pertinent peculiarity is explained in the narrative summary accompanying the local climatological data. Apparently, the station frequently experiences moderate to strong west to southwest winds which are sometimes Chinooks but more often are a drainage wind moving down the Yellowstone valley and thereby transporting warmer Pacific air into the area. At Bismark the difference is the relatively higher freeze-thaw frequency per year while the pattern as a whole dovetails very well with the Canadian station of Regina.

Around the Great Lakes there are several similar features in the freeze-thaw patterns extending west even to Minneapolis. Fall conditions are essentially alike at the five stations of Minneapolis, Madison, Sault Ste. Marie, Grand Rapids, and London. Similar winter patterns at Minneapolis and Sault Ste. Marie reflect more severe continentality, whereas Madison, Grand Rapids, and London have similar conditions. The latter two stations clearly show the moderating influences of the lakes with thaws of two or three days duration occurring each month. A major difference exists in the spring among these stations in which Minneapolis passes through the spring transition period very rapidly, whereas Madison and Sault Ste. Marie, somewhat less so. Again, Grand Rapids and London show the moderating effects of the lakes during March when for the better percentage of the years the cycles are regarded as freezes rather than as thaws.

On moving eastward, it is now possible to consider Albany as experiencing a similar air flow as over the lower Great Lakes.

The freeze-thaw pattern of Grand Rapids and Albany are very much alike. Further eastward, Boston shows marked maritime influence though with more severe weather conditions than are met on the west coast. Conditions at Yarmouth and Argentia show the modifications expected on the east coast in a more northern exposure. On the other hand, Buchans, Seven Islands, and Chatham are examples of freeze-thaw patterns of stations subjected to alternate maritime and continental conditions which are much more frequent on the east coast than on the west coast. Maritime conditions in the east do not usually extend far inland and Quebec City is a good example of a station having definitely more of a continental exposure.

The stations plotted, as previously stated, were to explore the more pronounced changes occurring between commonly understood geographic areas rather than to make the actual differentiation itself. Certainly, the contrast between the western maritime and the western mountains is most obvious. Less obvious is the transition between the high plains and the lower lying areas to the east. The Great Lakes area shows the maritime influence as does the east coast area and, again, is in rather marked contrast with the interior stations. In all, the profile across the continent does support the major premise of the expressiveness of the freeze-thaw process as an environmental parameter in climatology in that at least it is reflected by distinct geographic areas. Also, the differences are readily revealed by the station diagrams. How well areal differentiation is feasible or possible over a region expanded extensively to the north and to the south remains to be seen.

CHAPTER IV

FREEZE-THAW REGIONS OF ANGLO AMERICA

The west-east transect across the mid North American continent (Figure III) indicates the scale of contrast capable of being interpreted from the data. While much can be inferred from Figure III, there is insufficient geographic coverage to determine possible regionalization of the freeze-thaw phenomenon. Therefore, the area to be investigated is extended northward to Alert (82° 30' N) in the Northwest Territories of Canada and southward to Corpus Christi (27° 46' N) in Texas and Miami (25° 49' N) in Florida. The west-east extent continues to be from ocean to ocean. Comprising nearly all of Anglo-America, the temperature records for ninety-six United States stations, seventy-four Canadian stations and two Alaskan stations within the overall area are analyzed for frequency, duration, and severity of the freeze-thaw phenomenon. The two Alaskan stations are on the lower Pacific coast and are included to supplement the Canadian data. Locations of the stations used in this study are given by Figure IV.

Selection of stations is based primarily upon the desire for representative geographic coverage. Actually, the west coast, the mountain and plateau complex, the Great Plains, the Central Lowlands, and other geographic regions have several stations within their generally accepted limits. A careful final selection of stations permitted the more general features within each region to be covered.

To a degree, the diagrammatic method of presentation of the data places a relative limitation upon the number of stations that might be used. The limitation corresponds closely with the size of the base map and with the freeze-thaw diagram. Even so, in areas of high relief, it is still not always possible to place the diagram directly over its station location when using a base map of convenient scale. In this study the work maps are approximately 1 to 5,000,000 but a 1 to 7,500,000 scale is used for the final work map. For reproduction purposes this is further reduced to the scale of threshold legibility of the station diagrams. In this way it is possible to present data of several stations in each of the major regions subsequently delineated. On a corresponding scale, too, possible related phenomena of terrain, vegetation and climatic information are most readily available for comparative purposes. Desirable, perhaps, as finer detail may be, there would be the need for corresponding detail in the other phenomena and also the need for representative coverage of various geographic areas in order to support the major premise. On this detail, information is simply not readily available. However, this approach could well be used for further efforts when and if the major premise is found valid and has some corroborative support.

Diagrams of the freeze-thaw data for each of the 172 stations within the area under investigation are incorporated within Figure V and as indicated by the cross-continental strip of Figure III. Variations between widely separated stations or between stations of marked elevation differences are readily ascertainable. However, the actual placement of the boundary line more frequently depends upon finer differentiation. The scan, of course, depends upon the over-all similarity of the freeze-thaw pattern with the station just to the north, to the west, to the south, and to the east. Then details as to: (1) total frequency, (2) number of months of activity, (3) the transition and variable months, (4) the winter months of no thaws, (5) the durations - whether they are principally of one, two, three, or of four days, (6) whether these durations are more frequent as freezes or thaws, and (7) the severity of the freezes or thaws and the monthly season of greatest severity, assume importance. The diagram can be read not only for a great deal of pertinent information but also for a great deal of corroborative or noncorroborative information with respect to stations nearby or farther away. Upon the relationships discovered, nineteen major regions are delineated and of these, nine are further divided. The discussion of the regionalization follows.

Region I

The simplest delineation possible in the study is the boundary between areas where freeze-thaw does not appear in the monthly averages and the areas where it does. This occurs in two rather widely separated areas. First, Region Ia extends over the southern plains and prairies of Texas, lower half of Louisiana and the peninsula part of Florida. Second, Region Ib extends as a strip from Eureka, Calif., southward along the coastal range and inland to near San Bernadino and then southeastward to Yuma, Ariz. While activity of freeze-thaw does not show in the monthly averages, this does not imply that freezes do not occur in these two regions or that they may not be severe enough to influence or mold the landscape. The occurrence of the occasional freeze which creates such havoc among the specialized crops in these areas is quite well publicized. However, at this stage of the investigation, further subdivision of the data does not appear warranted.

Regions II, III, and IV

Another rather simple criterion is the separation of those areas where temperature regimes over the months are such that the activity of freeze-thaw is thought of only in terms of freezes, from those areas where, occasionally, the monthly activity is also treated as thaws. With this determining the northern boundary and with the southern boundary contiguous with Region I, the result is the three regions of II, III, and IV. Each of these three regions is further divided into subregions a and b on the basis of areas where freezes limited to one day duration are separated from areas where freezes of two or more days duration occur.

The southern border of Region II is contiguous with Region Ia while the northern border extends eastward from about Lawrence, Kan., to slightly north of St. Louis, Mo., south of Covington, Ky., across the southern Appalachians in the vicinity of Asheville, N.C., along the mountains to include the Piedmont area within the region and off the coast in the vicinity of Long Island. The boundary between the subregions of IIa and IIb practically parallels the northern boundary just described. The subregion boundary extends eastward across the southern portion of the Quachita Mountains, north of Chattanooga, Tenn., around the foothills of the Appalachians and off the coast in the general vicinity of Norfolk, Va. Total activity in IIa runs from the high of thirty-four freezes per year at Chattanooga to the low of two per year recorded at Pensacola, Fla. The activity does not extend beyond the five month period of December through March. As a rule, the freezes during March are very light. In general, December is the month of greatest activity but the month of February shows the largest departures. Minimum temperatures of 20 to 22° F can be expected during this month in many areas. In subregion IIb the total freeze-thaw activity increases from the low forties to the low seventies. Asheville, at 2090 feet, records seventy-two per year. Freezing conditions may occur as early as October and as late as April but the principal activity occurs during the four months of November, December, January, and February. Freezes of three days duration are to be expected west of the Appalachians and freezes of four days duration can be expected along the northern boundary. The extreme departures have shifted to the months of December and January but there is no sharp peak.

Regions IIIa and IIIb are contiguous with Regions IIa and IIb, respectively. The common boundary is delimited principally upon the differences between the temperature departure curves characteristic of the regions. In Region III the departure curve comes to a sharp peak. In subregion IIIa the peak occurs in February while in IIIb it occurs in January. But in Region II, the departure curves lack consistency and are either rounded, flattened or irregular.

The northern boundary of Region III extends from the mountain front eastward and then northeastward between Garden City, Kan., and Amarillo, Tex., and continues to the vicinity of Lawrence, Kan. The southern boundary is contiguous with Ia. The western boundary extends along the mountain front and again, the principal difference is in the temperature departure curve. To the west and southwest the curve has a double peak whereas Region III has a rather sharp single peak. The total frequency within subregion IIIa varies from fourteen at Dallas, Tex., to twenty-six at Big Springs. For subregion IIIb the frequency varies from forty-seven at Oklahoma City to sixty-seven at Amarillo. These are not significantly different from the frequencies in IIa and IIb, respectively. The activity also occurs practically during the same period. The principal difference is the temperature departure curves.

Region IV includes the interior valley of California and the southern part of what is known as the Basin and Range province. The region is divided into three parts; IVa, the lower area from Phoenix westward; IVb. the higher plateau areas represented by Winslow, Ariz., and Albuquerque, N.M.; and IVc, the slightly lower plateaus areas of Douglas, Ariz., and El Paso, Tex., to the south. In general, the yearly frequency in subregion IVa is quite low. Phoenix experiences on the average four mild freezes each year, San Bernadino five and Fresno seven. The temperature departures are but one or two degrees placing the minimum temperatures during the freezes around 26° F. The higher activity at Chico, Calif., and at Las Vegas, Nev., is evidence of one difficulty in a general treatment of this type. Certainly, the increased activity plus the increased number of months involved indicates the possible need for another subdivision but because of their relative isolation they must, of necessity, be placed in IVa. The occurrence of two day freezes and relatively high yearly activity definitely places the high plateau area in a separate subregion, IVb. Subregion IVc is separated from IVb by the previously used boundary between freezes of one day duration and areas experiencing freezes of two days duration. In turn, IVc is also separated from IVa by the relatively higher total frequency and by the increased number of months in which the activity is experienced. There is the contrast of two or three months of activity in IVa to the five months in IVc. El Paso and Alpine are somewhat of an anomaly within this area because both have topographic barriers to the colder winds from the north. The freeze-thaw activity in the more exposed areas would be more nearly similar to the pattern at Douglas, Ariz.

Regions V, VI, VII, VIII, IX, X, and XI

The two rather general limiting parameters for separating areas are: (1) areas where freezes are not of sufficient frequency to show up in the averages for any one particular month from areas where they do, and (2) areas where only freezes are considered to occur from areas where both freezes and thaws occur; both appear reasonable and logical. Furthermore, there has been no necessity to force or temporize the data to fit the general conditions imposed. But after the previous group of regions was delineated there appeared no readily discernible general parameter to delimit the next group of regions. It was only after boundaries were established on a station-to-station basis and the overall freeze-thaw pattern reappraised, that the next general parameter became evident. Actually, it follows in logical sequence from the second general parameter given above and becomes the zone where for at least one month the freeze-thaw is considered only in terms of thaws. In terms of relative winter severity, the southern limit of this series of regions corresponds to the freeze-thaw boundary which separates areas where only freezes occur from areas where thaws also occur occasionally (See Figure V). The northern limit reflects a temperature regime wherein only thaws are shown to occur for one month. The resulting general area is delineated into seven major regions.

Region V which barely satisfies the southern criterion extends along the west coast littoral between Eureka, Calif., to just north of Prince Rupert, B.C. The stations within this region meet the criterion by having one January in about every five or six years with a temperature regime such that the cycles will be treated as thaws. The synoptic pattern favorable for this situation would require an extended high pressure system over western Canada developing to the point where cold arctic air would spill over the mountain barriers to the coastal areas. The eastern border of Region V extends along the upper flanks of the coastal mountains. There is a very marked contrast between this region and the mountain complex to the east in terms of frequency, months of activity, severity, and, in fact, a complete difference in the patterns. The northern and southern boundaries are shown in Figure V as broad zones and this is a reflection of the gradual gradation usually met in west coastal areas. For such an extended north-south exposure, the range of the freeze-thaw frequencies is quite small, fifteen at Portland and twenty-four at Prince Rupert. The major difference within the region is the number of two and three day freezes at Prince Rupert. The other three stations experience only one two day freeze during the year. The departures at Prince Rupert are usually two to three degrees greater than elsewhere within the region.

Moving northward into Region VI as represented by the Alaskan stations of Juneau and Yakutat, there is a noticeable increase in the yearly frequency of the freeze-thaw activity. Juneau experiences fifty-two cycles per year and Yakutat, seventy-two per year. The two months accounting for much of the marked increase are March and April. Because the activity during these months is similar to that of the mountain areas, it could be concluded that the coastal areas are subjected to incursions of much colder air from the interior during this time. Actually, in the case of Yakutat, the situation during March would put the station into the next group of stations to be discussed because the activity is treated only as thaws. On examining the temperature data it becomes evident that the monthly minimum temperature is significantly reduced by the incursion of this much colder air but the air becomes rapidly modified by the maritime conditions to which the station is principally exposed. Because for the rest of the year the station is predominently reflecting the maritime exposure, Yakutat has been left within this general region and with Juneau is considered representative of Region VI. Another pertinent factor to the increased frequency is the occurrence of the process over a nine month period in Region VI as compared to four or five in Region V. Another marked change is the treatment of most of the activity during the winter months in terms of thaws. The marked dip in the departure curve during January and February is also significant. Region VI is quite different from Region V and also from the stations across the mountains. As with Region V, the eastern boundary is placed along the flanks of the coastal range.

Region VII is composed of the Appalachian mountains, the Cumberland plateau, lower New York state, and Connecticut. The yearly frequency ranges from fifty-seven at New Haven, Conn., at an elevation of 6 feet to eighty-one at Pulaski, Va., at 2189 feet. Freezes of two and three days duration are to be expected throughout the region and the activity extends over a seven months period in the higher elevations and a six months period elsewhere. The region is delimited from Region IIb by temperature regimes favorable for the occurrence of thaws and from Region IX to the north and west by the consistently milder winter conditions. The temperature departure curves have no definite characteristics within Region VII though they do show that the minimum temperatures of 18 - 20° F are not uncommon.

The east coast as represented by Boston, Mass., Yarmouth, N.S., and Argentia, Newf., comprise Region VIII. Synoptically, it is a region principally influenced by its marine location but still subjected to frequent incursions of colder continental air. The yearly frequency is forty-two cycles at Boston over a period of five months, fifty-two cycles at Yarmouth in six months and forty-three at Argentia over a similar period. Of the three, Boston is the warmest reporting station. The contrast between Region VIII and the area contiguous to the northeast is evident in the winter conditions, the length of time during which the activity occurs, and the total frequencies. The contrast is between an area where the average temperature is consistently below the critical zone for four months and Region VIII, where this occurs only part of the time for two months. Then the occurrence of the process over a period of eight and nine months is in contrast to the five and six months period in Region VIII. And, too, the yearly frequency which ranges from fifty-five to seventy-five is in variance with the forty-two to fifty-two cycles per year in VIII. While differentiation between Region VIII and IX is not quite so marked, it follows the same major trend.

Region IX is a rather narrow latitudinal strip extending from the Missouri River eastward across northern Missouri, southern Iowa, Illinois, Indiana, Ohio, southern Michigan, southern tip of Canada, the northwest section of Pennsylvania, much of New York state, Massachusetts, and the southern sections of Vermont and New Hampshire. Of significance is the rapid transition from areas to the south where the temperature is never consistently below the critical zone of 34° - 28° F to an area where the temperature regime is consistently below this critical zone, not for just one month but for three or even four months. Only frequent frontal activity and the passage of lows would account for such a rapid transition across the relatively narrow belt. The yearly frequency is in the sixties throughout the region and occurs over a period of six to seven months. Temperature departure curves change from rather rounded as at Peoria, Ill., and Akron, Ohio, to flat curves or to those with a marked winter dip such as occur at London, Ont., and Grand Rapids, Mich. This region as a whole is also characterized by the occurrence of freezes or thaws lasting as much as four days during practically every month.

Between Region IX and Region X is a triangular area with its apexes approximately at Lawrence, Kan., Sioux Falls, S.D., and Madison, Wis. Included within the triangle is Ames, Iowa. The area appears to be a transitional zone because it has no uniformity within itself, yet stations cannot be assigned to the contiguous regions. Synoptically, this is very possible since the area is in the path of the winter storms originating in Colorado as well as many storms moving into the United States from Canada. Possibly, too, superior air of Pacific origin could well be another factor involved.

Region X extends from the Missouri River to the Rocky Mountain front, and from about the Oklahoma-Colorado border to North Dakota and part of Montana. Yearly frequency is high and ranges from seventy-two at Billings to a high of 113 at Colorado Springs. Of the six stations within this region, only Billings has a total of less than ninety per year. Activity occurs over an eight to nine month period beginning in October and ending in April or May. Freezes or thaws of two and three days duration occur practically every month. The principal characteristic of Region X is the very large temperature departures occurring during the four months of November, December, January, and February, in which departures of eight to ten degrees are common. At Garden City and Colorado Springs these departures bring the minimum temperatures down to 18° to 20° F. On the other hand, maximum temperatures during the frequent thaws at Rapid City would reach 42° to 44° F which are mild winter temperatures for this area. In examining the variability shown as to possible occurrences of freezes or thaws, there is not as much north-south difference within the region as one would normally expect. Significantly, differences between Region X and Region IX are the higher freeze-thaw activity, its occurrence over a longer period, and the greater temperature departures of Region X.

The last major region within this general area is a large one encompassing much of the plateau area of the western plateau and mountain complex. The region is numbered XI and includes four subdivisions, a, b, c, and d, which meaningfully differentiate the freeze-thaw activity found within this vast area. Freeze-thaw activity ranges from a low of forty-six per year at Pendleton, Ore. (1494 feet), to a high of 168 at Durango, Colo. (6550 feet). The Pendleton area is so unique that it is delineated as a separate subregion, XIa, in which activity is principally that of freezes occurring over a seven month period. Temperature departures average six to eight degrees during colder months, but the departure curve shows a slight dip during December. In marked contrast to surrounding stations, temperature conditions at Pendleton are conducive to thaws in only one January in about every four. The subregion is very small and is represented in this study only by the one station.

Subregion XIb is in the lee of the Sierra Nevadas and is represented by the stations of Bishop, Calif., and Reno and Tonopah in Nevada. Although freezing conditions are again predominent, in about one January in every six or seven, temperatures at Bishop are favorable to the occurrence of thaws and even more often at both Reno and Tonopah during the months of December and January. Only occasionally do freezes last for two days, reflecting in general, conditions of nighttime cooling and daytime warming. Activity is high ranging from 103 at Tonopah and reaching 140 at Reno. Departures are moderate, falling within a six to eight degree range during the colder months of January and February.

Subregion XIc also has a high freeze-thaw activity ranging from ninety-eight at Klamath Falls to 168 at Durango. The common active period is eight to nine months, but the 168 cycles per year at Durango occur in seven months while the activity at Elkins lasts over a ten month period. Only four other stations in the study have such a record for continuous activity. Again, most of the activity is limited to one day. Only three stations show the possibility of a three day period and only Klamath Falls a possible four day thaw. Temperature departures reach eight to ten degrees, principally in November, since a slight dip is characteristic during December. The main difference in freeze-thaw characteristics between subregion XIb and XIc are the slightly higher frequency in XIc and additional months during which it occurs, the slightly larger temperature departures which show a slight dip during the colder month, and the greater number of thaw periods. In one respect, Milford, Utah shows an anomaly in that January is warmer than either December or February.

The fourth subdivision is XId which comprises the interior plateau of the southern Canadian mountains and the Columbia-Snake plateau area forming an arc to the south and west of the Northern Rocky Mountains. Activity ranges from fifty-four cycles per year at Spokane, Wash., to eighty-five at Yakima, across the Columbia plateau. At other stations, activity ranges from sixty-five to seventy-six. In all cases, freeze-thaw is restricted to a six or seven month period. Maximum departures reach six to eight degrees but also show the slight dip during the coldest month. Durations of three or four days occur at each station, although again, principal activity is limited to one day. Major differences between subregion XId and XIc are the lessening of freeze-thaw activity in XId, the fewer months in which the phenomena occur, the longer durations of the freezes and thaws, and the generally lower temperatures in subregion XId during colder months.

Conditions at Truckee, Calif., representing the crests of the Sierra Nevadas do not appear sufficiently distinctive to warrant establishing a new region. In several respects the diagram is very similar to that of Riverton, Wy., in Region XII. As January at Truckee records only thaws, the crest area should be in the same general region of XII, but as conditions would moderate to the southern Sierras, the crests as a whole are being considered, for the present, as part of subregion XId. On a larger scale, the Sierras could well be represented by several freeze-thaw characteristics.

Regions XII, XIII, XIV, XV, and XVI

The next common boundary delimiting a group of regions is the zone where for one month during winter the temperature does not reach or exceed 34° F. With regard to the diagrams, one winter month will show no activity. In general, the boundary extends from the zone separating Regions V and VI and continues eastward across the mountains to Fort Simpson, southeastward to Embarras, The Pas and Sioux Lookout, then swings north to the vicinity of Moosonee, south of Misstassine Post and off the coast around Seven Islands on the St. Lawrence Bay.

Region XII comprises the southern Canadian mountain complex and extends in two prongs into the United States forming a contiguous boundary with Region XI. The western prong extends as the Cascades and the eastern prong as the Northern Rocky Mountains. The freeze-thaw activity in this mountain complex is relatively high and ranges from eighty at Prince George (2218 feet) to 131 at Kleena Kleene (1950 feet). Butte has 122 cycles per year, Riverton 127, and Laramie experiences 118. The activity continues for ten months. Both Kleena Kleene and Butte experience an occasional frost in June. The predominent condition during the four months of December, January, February, and March is a series of thaws although this regime is not so rigid in the southern portion of the region. Temperature departure curves show the definite dip during December and January. Departures are only four or five degrees in the northern part but increase to a maximum of eight to nine at Riverton and Laramie. Durations of two and sometimes three days can be expected during the thaws but it does seem characteristic of mountainous areas that freezes are mostly of one day duration even though three and four day thaws are not uncommon.

In Region XIII, freeze-thaw activity ranges from forty-eight at Fort St. John to eighty-five at Lethbridge which is significantly lower than that at the stations in the mountain region. In other respects, the freeze-thaw diagrams of Region XIII and of Region XII are quite similar. This was not entirely unexpected since stations in both regions reflect isolated settlements commonly occupying sites in sheltered areas to obtain climatic conditions most amenable to man. Consider, for example, the similarity between Cranbrook in Region XII and Lethbridge in Region XIII. These two stations are at practically the same elevation, 3013 feet, as compared to 3018 feet; one is located in a mountain valley and the other in the lee of mountains. Differences that exist in the freeze-thaw diagrams can be attributed to the total frequency and the relatively milder winter weather at Lethbridge. This is ascertained from the departures at Lethbridge which are two or three degrees larger than those at Cranbrook. Also, about once in every six or seven years the cycle may be considered in terms of freezes during the three months of December, February, and March. Warmer conditions at Lethbridge may well be due to a similar explanation as for Billings; that is, the occurrences of Chinook winds and with these the incursion of warm, dry superior air from across the mountains. As similar as these two stations appear to be, Prince George (2218 feet) in Region XII and Edmonton (2219 feet) in Region XIII are more nearly alike. Differences in total frequency are about the same, (21 as compared to 18); and similar differences in temperature departures occur for both stations, two or three degrees. The winter temperature regimes at the two stations are practically the same, for both experience a four month winter period during which the temperature regime is such that the activity is considered only in terms of thaws. Total activity is very comparative.

The difference between subregion XIIIa and XIIIb is the relatively colder and longer winter period in b. November is a variable month but in a the cycles as a series of freezes are more frequent whereas in b the cycles in terms of thaws are more frequent. The thaw activity decreases significantly in that during January only one may occur. The temperature departures are smaller and the maximum temperature during the January thaw would reach only 36° F or 37° F.

Region XIV is another triangular region although unlike the triangular transitional area at Ames, Iowa, Region XIV has characteristics which permit delineation from contiguous regions. As compared to Region XIII the total frequency decreases and becomes consistently in the forties. Winnipeg experiences forty-six cycles per year. The winter regime is definitely colder in terms of freeze-thaw. The number of thaws during December, January, and February is limited and departures during these months are two to three degrees smaller than in Region XIII. Winnipeg shows the extent of its continentality by the rapidity with which the freeze-thaw transition takes place. The transition months are October and November in the fall and March and April in the spring. The change-over is not quite so sharp as in the area to the north but is shorter than in Region XIII to the west and Region XV to the east.

Region XV has characteristics attributable to the incursions of colder air from the west and north and of warmer air from the south. The winter dip characteristic of the temperature departure curve within this general area is evident here, but there is a moderation from the western border (Region XIV) to the eastern border (Region XVI). Following the departure trend, the number of winter thaws also increases from west to east. The yearly frequency remains in the forties but there are two stations which definitely reflect the influence of the cold waters of Lake Superior. These are Franz, Ont., which experiences seventy-six frequencies over an eleven month period, the longest period of continuous activity recorded in the study, and Iron Mountain, Mich., with sixty-two cycles per year. Both stations are in close enough proximity to the lake to be influenced by air with a fetch from off the lake, yet far enough inland so as not to be dominated by the lakes as is the case of Sault Ste. Marie. Another apparent anomaly which should be mentioned is the placement of the northern boundary in the vicinity of Moosonee, at the southern tip of St. James Bay. This boundary is determined principally by the April regime at the station. The regime shows the moderating influx of warm air which could come only from the south during the passage of rather extensive lows moving along the St. Lawrence valley. April patterns at Nitchequon and Mistassine Post also reflect this synoptic pattern. At the eastern boundary of the region, Ottawa and Quebec show a very sharp spring transition period in contrast to usual conditions found in Region XV. It is as though these two stations are in the actual transition zone to Region XVI.

Region XVI is a long corridor having Region XV to the west and north and Region VIII to the east and south. It is situated between two storm tracks, one along the St. Lawrence valley and the other off the Atlantic coast. The total freeze-thaw activity is rather high, ranging from fifty-four at Burlington, Vt., to seventy-six at Berlin, N.H. Activity extends over a period of eight to nine months which is the same as in Region XV, but longer than either Region IX to the south, or Region VIII to the southeast. Region XVI continues the general winter temperature regimes of Region XV but the severity is moderated by frequent thaws. For practically one-third of the days during these four months, the maximum temperature can be expected to reach the 38° F to 42° F level with two and three day thaws experienced every month. Considering the similarity of the freeze-thaw pattern of Region XVI with those of Region IX, it can be inferred that the thaws result from the influx of warmer air from the southwest. Region XVI differs from Region XV principally in the general increase in the freeze-thaw activity, the more frequent winter thaws, and the larger temperature departures. Instead of the characteristic dip, the curve has now a relatively flat top during the winter period.

Regions XVII, XVIII, and XIX

The common characteristic of the three remaining regions is the prolonged cold winter period. Region XVIII comprises the northern section of the Canadian mountain complex. Here, the yearly freeze-thaw activity ranges from forty-seven at Dawson to seventy-two at Snag. Each station experiences three months when the temperature does not reach 34° F and a fourth month when this occurs only once or twice. The fall period shows a sharp transition through the critical temperature zone, but the spring transition is not quite as rapid. Temperature departures are small but for one month in the fall and another in the spring, in which departures amount to about eight degrees. This region is subdivided with one subdivision comprising the mountain ring and the other the interior plateau. The plateau area shows more moderate and uniform regimes. Total activity is in the fifties, and both the fall and spring transition periods are not as pronounced as in subregion a. Very light thaws may occur about once or twice a month during the colder season.

Region XVIII is an extensive latitudinal strip north of but contiguous with Regions XIII, XIV, XV, and XVI described in the previous section. Freeze-thaw activity ranges from thirty-three at Fort Reliance to fifty-two at Nitchquon. Region XVIII has the sharp transition in the fall which appears as a characteristic of northern continental exposures. Here again, the spring transition period is not quite so sharp. Freeze-thaw activity is concentrated in the transition periods as there are only a few months during colder weather when thaws do not occur, and only a few months during warmer weather when freezing conditions do not occur. During these transition periods, freezes or thaws of two and three days duration occur in which temperature departures may be from four to six degrees. The most distinctive graphic characteristic of the temperature departure curve is that the curve becomes two rather short segments. Region XVIII has a subregion along the coast of Labrador. The diagrams indicate the influence of open water by the longer fall transition period at Fort Chimo on Ungava Bay and the longer spring transition period at Goose Bay under the influence of the open water of the North Atlantic Ocean.

The freeze-thaw patterns within the northern area of Canada indicate the desirability of dividing the total area into two regions. This is done on a rather relative basis considering principally the transition of the pattern characteristics of XVIII to the broadly uniform pattern of the more northern territory. On a station-to-station comparison, the boundary is placed so as to extend from the western mountain complex at Norman Wells, eastward across Great Bear Lake, southeastward to the vicinity of Churchill, across Hudson Bay, Ungava Bay and off the coast at the northern tip of Labrador. Included in Region XIX is the area in the northwest represented by Aklavik and Old Crow. Reflecting the long, cold winter, the freeze-thaw cycles cease after October and begin again as late as April and May. As compared to Region XVIII the winter period without thaws is longer by two or three months. Total frequency is limited to eleven at Eureka but reaches the high of thirty-six at Clyde River on the Baffin Bay coast of Baffin Land. Again, these are relatively lower than in the region to the south. Reflecting the lower yearly total is the number of months in which the activity takes place. Generally, this is two in the fall and two in the spring which also indicates the rapidity of the transition through the temperature zone of 34° F to 28° F. Another feature of this most northern region is the light intensity of the freezes and thaws. Departures average only two or three degrees. The east coastal area is again designated a subregion and reflects the moderating influence of the open water of Baffin Bay. Activity is higher and the transition periods are slightly longer. Although most of the stations of this region are located near water, there is a difference between the western stations exposed to the influence of the Arctic Ocean and the eastern stations exposed to the waters of Baffin Bay and Davis Strait. It would appear that the pack ice accumulates rapidly in the Arctic Ocean thereby making the transition to continental conditions very sharp. On the other hand, the Baffin Bay must remain open longer and is influential in increasing the total frequency of the freezes and thaws on its shores.

Discussion

The boundaries incorporated into Figure V were initially determined on station-to-station relationships. On reviewing the overall pattern, it became evident that several regions would have their northern and southern boundaries determined on the same basis. In essence, this basis is break-points in the increasing severity of climate from south to north in terms of freeze-thaw. As reasonable and logical as these may be, they are in no sense, for the present, more valid or more important than the criteria used in determining the east-west divisions even though these criteria are more varied and perhaps represent a more intricate intertwining of factors. Since the map was prepared from temperature data that is strictly representative for a small area, interpolation between stations on the scale used in this study is mainly subjective. Although the boundaries thus delimited may be moved slightly between stations and still satisfy the conditions for which they were drawn, there is a marked representativeness for the overall regional pattern.

Though the overall freeze-thaw pattern is representative, a number of unsettled questions remain. The crest of the Sierra Nevadas as represented by Truckee is one. There is a certain degree of similarity between Truckee (5982 feet), Elko, Nev. (5075 feet), and Riverton, Wy. (4954 feet), especially during the late winter and spring conditions. However, differences appear in the fall pattern and in the temperature departure curves. This does raise the question of the effects of marked topographic control. Truckee is an isolated ranger station sited just in the lee of the Sierra Nevada crest, whereas both Elko and Riverton are sited in valleys. In the descent from Truckee to the more protected site of Reno, the freeze-thaw pattern changes markedly. Then it is very possible that on ascending from the valley sites of Elko and Riverton, more severe freeze-thaw conditions are to be met at more exposed sites in the nearby mountains. Keeping in mind the limits imposed by the data available, it becomes obvious that what is being measured and compared on a relative basis are the favorable sites for settlements. Another problem arises when two rather widely separated stations have somewhat similar freeze-thaw patterns. Two such pairs could be Tonopah, Nev. and Garden City, Kan.; and Yakima, Wash. and Williamsport, Pa. and there are several more. What might be the possible significance of such similarities needs further study not only with respect to the general climatic conditions of the area but also to the local climate as well. Freeze-thaw is not a dimensionless number but a finite physical process which has several measurements and these measurements reflect the integrated total of climate at the time the process takes place.

In most respects, Figure V gives positive and valid support to the objectives of this research paper. Based upon gradations of freeze-thaw activity, regionalization is not only possible but is orderly. Furthermore, the differentiation is not forced or arbitrary, but is suggested by the data. In this, the diagrammatic presentation is most helpful. Differences between stations or similarities among a group of stations are easily ascertained by visual inspection. Groupings suggest regionalization while differentiation of the differences makes regionalization possible. The analysis of the temperature records is simple and direct. There appears no need for more than the basic factors of frequency, duration, severity, and type. These proved adequate for this study.

It does appear that the overall pattern in Figure V follows an orderly and logical sequence of development. This in itself is a major support to the substantiation of the initial premise. The significance of the differentiation between regions and subregions would be helped considerably by corroborative data. This is the subject for the following chapter.

CHAPTER V

CORROBORATION FOR FREEZE-THAW REGIONS

To accept the postulate of order in the variation of the freeze-thaw pattern from place to place is to reintroduce the question of its association with other phenomena in the natural environment. As a measure of climate the freeze-thaw pattern should be reflected in the areal distribution of climatic elements. As a connecting link between climate and the landscape, the imprint of freeze-thaw should be recognizable in individual features. If an association can be shown to exist with climatic elements on the one hand and with features of the landscape on the other, then the concept of freeze-thaw as propounded by this study is well substantiated.

Precipitation

An effective moisture measure is an elusive figure as attempts by Koppen and Thornthwaite well attest. Simplicity may provide a better approach. Thus instead of depending upon an index number with arbitrarily chosen limits, this study uses the same approach as with the freeze-thaw data in that dependence is placed upon relative comparisons of significant components of precipitation activity. Significant levels of information pertaining to precipitation would appear to be the amount, the number of days with precipitation, and the intensity of the precipitation. These factors are not new to climatology. Recently, Russak and Easley (28) proposed a method for estimating the frequency distribution of precipitation rates directly from the mean annual precipitation, and the number of days with precipitation. Thus it can be assumed that the precipitation factors to be considered in this study are basic. These are: the mean annual amount, the mean number of days recording a trace or more of precipitation for each of the twelve months, and the average intensity of precipitation by months.

The data are again presented in diagrammatic form which is illustrated by Figure VI using precipitation figures for Burlington, Vt. In the diagram the base line extends from July, December (D), January (J) and June corresponding to the sequence in the freeze-thaw diagram. The monthly amount of precipitation in inches is plotted above the base line and the number of days with precipitation is plotted below the line. The curve incorporated within the diagram is the average daily intensity of precipitation for the month. It is obtained by dividing the monthly amount by the number of days with precipitation. Frequently the curve obscures the monthly amount, so for clarity in these cases, a dashed line is adopted for the base. This curve is useful as an indicator of the intensity as in most cases the space between the two lines equals an intensity of 0.15 inches per day for the month. In just a few cases, this either becomes 0.30 or the dashed line is not needed for clarity. These exceptions are obvious on studying the particular diagrams. As can be seen the possible variations are infinite. But by anticipating a degree of orderliness in the pattern variation from place to place, the probable number of variations is drastically reduced. The upper

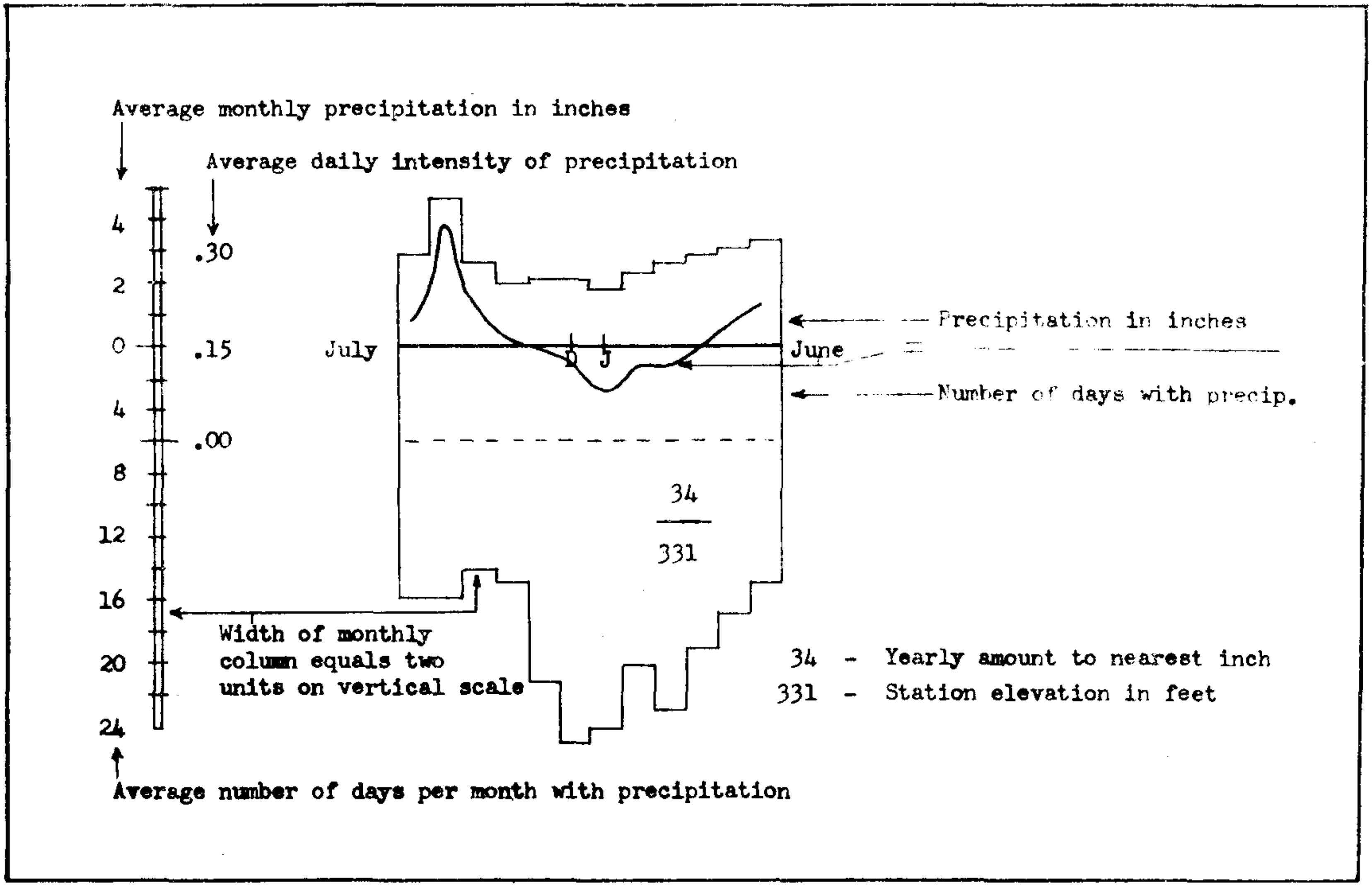

Figure VI - The Precipitation Diagram

of the two numbers associated with the diagram is the yearly precipitation to the nearest inch and the lower figure the station elevation in feet.

As with the freeze-thaw data, the precipitation data lend themselves to a degree of grouping among stations and to a degree of differentiation from other stations. This again suggests regionalization. A study of Figure VII should clarify this latter point. The data presented are for the same stations and for the same time period as for the freeze-thaw phenomenon. The discussion of these precipitation regions and their differentiation follows.

Beginning in the western littoral, precipitation data also divide this extensive strip into three regions: northern, central and southern. The northern region (I) extends southward from Yakutat, Alaska, with the eastern boundary along the crests of the Pacific coastal ranges to within the lee of Vancouver Island, down the mountain flanks southward to include Vancouver Island and the Olympic Mountains and then off the coast around the mouth of the Columbia River. The coastal exposures of this region have extremely high yearly amounts of precipitation, usually well over 100 inches per year. Another pronounced characteristic of this region is the marked seasonal distribution of the precipitation which reaches its maximum during the period of August through December in the north, and shifts to the months of November through February at the southern border. As much as 16 to 20 inches of precipitation per month may be recorded at the more exposed stations during this period. However, there is only a slight trend toward a corresponding increase in the number of precipitation days per month with the increased monthly precipitation occurring mainly during the winter. The southernmost station within the region is an exception; otherwise, months with twenty or more precipitation days are the rule at Yakutat. This same regime occurs for more than half of the months at Juneau and Prince Rupert but for only five months at Pachena Point. The latter station shows a definite increase in the number of days with precipitation corresponding with heavy precipitation during these months, while average daily intensities remain high. For the five months at Yakutat and Pachena Point the daily intensity averages more than 0.50 inch of precipitation. The sheltering effects of promontories or islands are amply illustrated by the comparison between Pachena Point and Vancouver. The former receives 127 inches of precipitation per year while the latter receives only 42. In terms of the number of days with precipitation the difference is not nearly as great. Vancouver has slightly fewer precipitation days during late summer and early fall. Thus, precipitation patterns are sufficiently different for Vancouver to be placed in the contiguous region to the south, the central region (II).

The central region (II) extends from the flanks of the Pacific coastal range in the lee of Vancouver Island southward with the eastern boundary again along the mountain crests. The Sierra Nevadas also are a part of this central region. The boundary delimiting this region curves back northward along the lower western slope of the Sierra Nevadas and then intercepts the coast at Point Arena, Calif. Within this region, the precipitation ranges between 40 and 50 inches per year and is characterized by a marked winter maximum. Another notable feature of the precipitation regime is the beginning of a short summer dry period. The pattern showing the number of days with precipitation is almost a mirror image as the pattern of recorded precipitation. The maximum number of days with precipitation is around twenty occurring during the winter months. There are considerably fewer days of rain during the summer months. Intensities for much of the rainy season are also lower but still amount to over 0.30 inches per day. During the summer months intensities drop to less than a third of this figure and are even much less at Eureka.

The southern west coastal region (III) includes the low coastal ranges to the United States-Mexican border, the interior valley of California, the western flanks of the Sierra Nevadas and its southern extremity. The marked winter maximum of the precipitation remains a characteristic even though the yearly totals are now less than 10 to 12 inches over much of the area. However, during the middle of the rainy season, daily intensities may be only slightly less than those experienced in Region II. The long summer dry period with little or no rain has become another major characteristic of this region. Because of the higher annual amount of precipitation, the northern half of the interior valley is considered as a subregion within the overall southern littoral region.

The definite contrast between the conditions over the western littoral and the mountain and plateau complex indicates that little of the excess moisture along the coast precipitates within the mountain-plateau complex. The latter region is characterized by its generally low amounts of precipitation. Favorable areas may receive as much as 18 to 22 inches per year, but much of the region receives 10 inches or less. The distinguishing feature within the complex is the manner in which this small amount is distributed throughout the year. It principally varies from winter minimums in the northern reaches to winter maximums in the central areas, and back again to winter minimums in the extreme southern sections. The total amounts received follow a somewhat similar pattern.

Essentially, there are seven regions within the mountain-plateau complex, three in Canada and four in the United States. The northern region (IV) in Canada comprises the mountain area north of an east-northeast line between Juneau and Fort Simpson. Yearly precipitation ranges from 9 to 13 inches with a summer maximum and a slighter secondary maximum in mid-winter. The minimum is in the spring. The number of days with precipitation follows a similar pattern with precipitation days per month ranging from fourteen to twenty during the two precipitation periods and ten or less during the spring months. Average intensity decreases from the maximum in the summer to a minimum in the spring but at all times it is quite low with only a few months averaging 0.10 inches per day or more. The central Canadian mountains comprise Region V in which yearly precipitation amounts to 17 to 22 inches with the winter maximum equalling or exceeding the summer maximum. The minimum still occurs in the spring. The distribution of the number of days with precipitation remains about the same as in the region to the north and the spring minimum is usually retained. Intensities are uniformly higher than in Region IV and values between 0.10 and 0.15 are most common. The southern area (VI) comprises the third mountainous region within Canada. The yearly range decreases to 14 to 19 inches with even further reductions being present within well sheltered valleys such as at Ashcroft which records only 9 inches for the year. The pattern of amount of precipitation is characterized by a winter maximum with secondary peaks occurring during June and August. July is characteristically dry as are late fall and early spring. The number of days with precipitation is drastically reduced with a yearly distribution that is fairly uniform. Peak intensities reach 0.25 inches per day during the winter and show a gradual progression from the low of around 0.05 in Region IV, to 0.10 - 0.15 in Region V, and 0.20 - 0.25 in Region VI. The sequence follows the relative increase in the winter precipitation between the three regions.

Within the United States, Region VII is composed of the Columbian plateau, the northern half of the basin and range province and the western section of the Colorado plateau. The pattern shows a marked winter maximum in amount received and in the number of days in which it occurs. There is also a trend toward a secondary maximum in late spring or early summer. Minimums occur in late summer and early fall. There is a marked similarity in the pattern between this region and the western littoral region (II). In contrast, however, plateaus and basins receive annually only 9 to 17 inches of precipitation, or only a third of that which falls in the coastal area. The number of days with precipitation may reach eighteen or twenty per month in the more exposed stations during the winter and may drop as low as twelve as, for example, the sheltered station of Reno. Precipitation amounts to about 2 inches during each of the months of December and January. In contrast to Region VI to the north, intensities are much lower with values around 0.10 inches per day predominating. Lost, too, is the winter peak, except at Reno, where the explanation seems to be the fewer days of occurrence rather than additional amounts of precipitation. The southwest section of the basin and range province comprises Region VIII, the second region within this complex. Yearly precipitation ranges from less than 2 inches to about 6 to 7 inches. Gone is the winter maximum; instead, there is a trend toward a slight maximum in July which shows more strongly in the number of days with precipitation than in the actual amounts received. The number of precipitation days remains low throughout the year with Yuma recording seven or less and Milford with nine or less during any one month. Even with the fewer precipitation days, intensities remain low being 0.10 inches per day or less during most of the year in this region. In terms of winter precipitation and intensities of precipitation, the transition to conditions similar to Region IV is almost complete.

The southeastern section of the basin and range province and the southern section of the Columbian plateau comprise Region IX.

Yearly amounts are between 4 and 8 inches, and the principal characteristic is a very marked July-August maximum with an accompanying increase in the number of days with precipitation. Precipitation during July averages around 1½ inches at Winslow and Phoenix and over 4 inches at Douglas and precipitation days range from thirteen at Phoenix to nineteen at Douglas during this month. For the rest of the year both the amount and precipitation days remain quite low. Intensities are rather irregular and probably reflect the sporadic nature of the precipitation regime within this region. The Rocky Mountain complex comprises Region X or the fourth region in the United States within the overall mountain and plateau complex. The characteristics of a winter minimum and summer maximum contrast with the winter maximums and summer minimums in the regions to the west and to the north. Yearly amounts remain low, averaging between 8 and 12 inches though Durango is favored with 17 inches per year. In fact, Grand Junction and Durango on the Colorado plateau may well be in a transitional area. Both reflect the winter maximum characteristic of Region VII and Durango has the marked increase in the number of days with precipitation during July and August characteristic of Region IX. As a result, a small transition area is being shown by Figure VII.

Precipitation Region XI is rather an elongated strip in the eastern lee of the Rocky Mountain and the Intermontaine basin plateau complex. Principal characteristics are winter minimums in precipitation amounts, in number of precipitation days, and in intensities of precipitation, and summer maximums in these characteristics. The diagrams of Figure VII show the contrast between summer and winter conditions very well. Yearly totals in this region range between 11 and 21 inches. The major difference between Region XI and Region XII to the north is the very marked increase in the number of precipitation days during the winter season which may now equal or exceed the number of precipitation days during the summer rainy period. However, this increase is accompanied only by a barely noticeable increase in the amount of precipitation during January. In terms of total amount and the distribution of the precipitation the two regions are very similar.

Region XIII is principally a transitional area between Region XI to the west and Region XVI to the east. As a consequence, Region XIII has no distinct characteristics applicable to the region as a whole, yet the stations do not wholly belong to either contiguous area. Lawrence, for example, has a precipitation distribution similar to that of Region XI but shows a relationship to Region XVI by its spring pattern in an increased number of precipitation days. Further south, the winter precipitation also begins to show the characteristics of Region XVI as these stations lose the marked winter characteristic of Region XI. Region XIII has the contrast between central and eastern sections of Texas. Laredo and Corpus Christi show a precipitation and intensity distribution similar to that of Region XI, though modified to a fall maximum in precipitation and intensity and, too, a short dry period is shown for July. Differences are sufficient to be incorporated within a subregion. On the other hand, Dallas and Austin possess spring patterns more closely aligned with Region XVI. While the contrasts across the region are quite marked, the differences are not considered sufficiently sharp to warrant the use of a single boundary.

Region XIV has the best example of the development of summer concentration of precipitation and its intensity in contrast to prevailing winter conditions. During June and July 4 to 5 inches of precipitation occur in fourteen to sixteen days with intensities averaging about 0.30 inches per day. In winter 1 to 2 inches occur and the intensities drop to less than 0.05 inches per day. However, like Region XII to the west, the greater number of precipitation days occurs in winter even though precipitation days occur about half the time throughout the year. Duluth experiences five months with twenty or more days when precipitation is recorded, and Madison has five months with sixteen or more days. Total amounts range from 26 inches at Minneapolis to 34 inches at Peoria. The distinction from the region to the west is principally in the greater winter precipitation as well as in larger summer amounts. Also, there is the characteristic of increased number of precipitation days especially during the spring and early summer.

On scrutinizing Regions XV, XVI and XVII it becomes evident that the eastern half of the United States and the eastern half of southern Canada are under the influence of a different precipitation regime. Beginning the regionalization from the southeastern states, Region XV, it is seen from the Miami diagram that the area is characterized by a late summer and early fall maximum in the amount received, the number of days with precipitation and the intensity of the daily precipitation. A winter minimum is evident in these features. Six to nine inches of rain may be recorded each month during the wet period; the amount then drops abruptly to 2 to 3 inches during the winter dry period. The number of precipitation days also decreases abruptly from sixteen to twenty each month down to six to eight during the winter. Along the Atlantic coast the Miami pattern begins to be modified by the Charleston area, and in the Norfolk, Va., area only a noticeable trace of the fall pattern remains. On the Gulf coast, the transition to conditions of Region XVI is more rapid as the winter pattern records increased precipitation but only a relatively few more precipitation days. As a result, daily intensity during winter almost matches summer conditions. The boundary between Regions XV and XVI extends northeastward from the vicinity of New Orleans to about Washington, D. C.

Region XVI is characterized principally by a fall dry period and ample amounts of precipitation during the remainder of the year. Intensities are consistently high and range between 0.30-0.40 inches per day or more depending upon the number of days with precipitation. Days with precipitation may be as low as eight a month but rarely exceed twelve. As a result exceptional periods of fair weather occur, considering, particularly, that total precipitation reaches about 57 inches per year in the south and 35 inches in the north. The northern boundary extends eastward from the vicinity of Peoria, Ill., to Covington, Ky., and thence to the Appalachians through the general area of Elkins, W.Va.

The principal characteristic of Region XVII is the uniformity of the precipitation received over a year's period. This pattern differs from Region XIV to the west in that now winter precipitation equals or approximates the summer regime. The two regions, however, have in common a pronounced maximum of precipitation days during colder months due to the influx of moist air from Region XVI to the south and from the Great Lakes within the region. The moist air flux continues down the St. Lawrence corridor and occasionally reaches northward even to the St. James Bay area. As a consequence, the northern boundary extends from north of Lake Superior to Moosonee, southeastward to Mistassine Post, then northeastward to Goose Bay and off the coast of Labrador. The Moosonee, Val d'Or and Mistassine Post area actually is a transitional zone sharing characteristics of Region XVIIa and also of Region XX to the north. Here, the winter pattern shows the effects of an occasional influx of moist air from the south, yet the general pattern is quite similar to that of Region XX. The St. Lawrence corridor is designated a subregion because of the slight winter maximum of precipitation shown due to the influx of moist Atlantic air during this period, thereby imparting overtones of the characteristics of Region XIX located along the Atlantic coast.

Regions XVIII and XIX extend along the Atlantic coast southeast of Region XVII. Region XVIII emerges as a gradual changing pattern from Region XV to the pattern of XIX. Region XVIII incorporates in its southern station a noticeable trace of the early fall maximum in the amount of precipitation and in intensities. In addition, it has relatively fewer precipitation days characteristic of areas to the south and southwest. In the north, however, the pattern loses the fall maximum of precipitation and incorporates the trend to a winter maximum characteristic of Region XIX. There is also an increased number of precipitation days which is again a feature of Region XIX. The principal difference between Region XIX and XVIIb is the more pronounced winter maximum of precipitation and the slightly higher intensities received in the former. Total precipitation averages between 47-55 inches in Region XIX in contrast to 33-43 in Region XVIIb. Even though the number of precipitation days in the two regions follows practically the same pattern, daily intensities in Region XIX average 0.05 to 0.10 inches per day higher than in Region XVIIb.

The two remaining regions to be described are commonly known as the arctic and subarctic regions of Canada. Most of the northern region (XXI) receives less than 9 inches of precipitation per year, with the northwest section receiving less than half of this amount. A late summer or fall maximum is characteristic with a midwinter minimum. Intensities during the winter are very low. The number of days with precipitation usually shows a definite maximum during late fall and early winter. Similar to the pattern of freeze-thaw there is increased activity along the shores of Baffin Bay and the Davis Strait. Here, annual amounts increase to 10 to 17 inches and while the maximums still occur during late summer and early fall, the winter period also shows increased activity. The arctic, delimited by the precipitation data follows closely the boundary determined from the freeze-thaw data. Thus, the line extends along the Brooks Range to Norman Wells, then eastward across Great Bear Lake to Port Radium, southeastward past Fort Reliance, and finally turning just south of Ennadai Lake, north of Churchill, across Hudson Bay to the southern tip of Ungava Bay and off the Labrador coast. The eastern shores are again considered as a subregion of the arctic. The subarctic extends in a broad arc south of the arctic. The western boundary is the Canadian Rocky chain where annual precipitation ranges from 14 to 15 inches whereas on the eastern extent of the Labrador shores, yearly precipitation is twice this amount. In the west, there is the characteristic summer maximum and winter minimum which gradually shifts to an early spring minimum in the eastern sections. Throughout the entire region, the number of days per month with precipitation shows the characteristic late fall and early winter maximums. From the diagrams there does not appear to be any definite east-west breaking point within this region.

The total analysis of precipitation patterns of Anglo America results in twenty-one regions in which only four are further subdivided. Similar to the overall pattern of the freeze-thaw phenomenon, there is a degree of orderliness in the variations from place to place. The question naturally arises as to what degree the same orderliness occurs in both the patterns. Perhaps more to the point, what is the degree of similarity between the two distributional patterns?

Figure VIII is prepared by superimposing the precipitation pattern of Figure VII upon the freeze-thaw pattern of Figure V. As can be seen, practically an exact superimposition occurs along the Rocky Mountain front of the great western plateau and mountain complex as well as along the crests of the higher Pacific coastal ranges and the Sierra Nevadas. The Appalachian ridge and valley province, however, which is revealed in the freeze-thaw pattern is not reflected in the precipitation pattern. Another boundary that is almost in exact agreement is that delineating the northeastern maritime coast. Cape Cod area, the Atlantic strip of Nova Scotia and of Newfoundland are delineated as a region in both patterns. Additional boundaries in close agreement are the southern limits of the arctic region and the delineation of a separate subregion along the Baffin Bay coast. A significant difference occurs in the arctic boundary near Ennadai Lake and Churchill. According to the freeze-thaw pattern, Ennadai Lake is in the subarctic whereas Churchill is classified as arctic. The precipitation pattern, however, reverses the classification of these two stations. It appears that the zone of climatic transition is rather wide, perhaps to the extent of 75-100 miles or so. Additional station records need to be analyzed to clarify the situation.

A similar condition exists along the southern boundary of the subarctic extending from Moosonee, to Val d'Or and Mistassine Post. Again, the difference in location of boundaries is not extreme being only 100-125 miles at the most. According to the precipitation analysis, the area is considered transitional and there is some justification for a similar consideration in terms of freeze-thaw even though this is not indicated in Figure V. Both methods delineate common boundaries for the western extension of the subarctic which separates the northern reaches of the Canadian mountains from the central region and the northernmost littoral from the middle Pacific coastal region. Of course, in this area the freeze-thaw boundary delineated is rather a broad transition zone, but, nevertheless, the extension of the subarctic boundary determined by the precipitation forms the northern limits of the freeze-thaw transitional zone. At the eastern section of the subarctic boundary a divergence occurs. The precipitation boundary turns northward perhaps because of the circulation associated with the lows off the Newfoundland coast, whereas the freeze-thaw boundary is forced off the land by the incursion of cold winter air. The moderating influence of southerly flow is not felt during the winter because here the principal flow has a westerly component. Even a southwesterly flow would not provide for sufficient open water fetch as to be effective.

Another common boundary is that which follows rather closely the course of the Missouri River separating freeze-thaw regions of X and XIII and precipitation regions XI and XII. In the central part of the United States, a freeze-thaw boundary is incorporated within the precipitation transitional zone of XIIIa. However, starting at the common point of Sioux Falls and extending northward to Winnipeg the two boundaries diverge at a rather small angle. The principal areas of difference are in the eastern United States where the freeze-thaw boundaries are usually east-west and the precipitation boundaries are southwest to northeast. In the mountain and plateau complex the boundaries again transect.

The extent of agreement between the two maps of freeze-thaw and precipitation is considered significant. Since the coincidence of boundaries independently derived establishes that freeze-thaw is a climatological parameter with respect to at least one accepted climatic element. In the discussion of Figure V it was pointed out that there is a degree of subjectiveness in the placement of the boundaries between stations. The same degree of subjectiveness is also incorporated in Figure VII. It is believed that if the freeze-thaw and the precipitation data are analyzed as a unit, a better regionalization of the combined product is possible. However, to analyze the two maps as a unit would negate the usefulness of the individual precipitation map as a corroborative support to the delineated freeze-thaw regions.

Vegetation and Soils

Further corroborative support for the significance of freeze-thaw should be found if a recognizable degree of coincidence exists between the regional distribution of freeze-thaw and the regional distribution of natural vegetation and soils. With time, the physiological stresses imposed by freeze-thaw might well have contributed to natural selection of vegetation within a given region. For example, several southern species are extremely susceptible to freezing conditions, and even in northern areas, a sudden late spring freeze can cause extensive foliage damage. Spurr (32) presents a graphic description of such a freeze upon various tree species in the Harvard Forest located in central Massachusetts. Thaws can also produce destructive stresses to vegetation. MacHattie (24) attributes the foliage damage in lodgepole pine, spruce, and Douglas fir, which frequently appears as a reddish-brown band on various western mountain slopes, to a sudden rise in winter temperature usually associated with Chinook winds followed by dessication. He maintains that the sharp temperature rise must precede dessication in order to account for the observed banded distribution of foliage injury. Benninghoff (5) in reporting his investigations made in the arctic regards dessicating winds as contributing to differences existing in the tree-line between exposed and sheltered sites in the subarctic and arctic.

Data on the distribution of natural vegetation permitting station-to-station analyses comparable to those used in investigating freeze-thaw and precipitation are not available. Nevertheless, an exploratory comparison was made using a vegetation map of Anglo America adapted from Lewis and Campbell (20), Baker (3), and Kuchler (15). In Figure IX the freeze-thaw regions of Figure V are superimposed upon this vegetation map. General agreement of boundaries occurs along the higher crests of western mountains, along the eastern front of the mountain-plateau complex, and generally along any marked elevation contrast. In the East, freeze-thaw, precipitation, and vegetation share a common boundary along the Atlantic littoral of Nova Scotia and Newfoundland. In the North, a common boundary appears to delimit the arctic tundra from the subarctic coniferous forest to the south. In the West near Bear Lake, the southern limit of the subarctic is similarly delineated. However, over the remainder of Canada and the United States, agreement between vegetation and freeze-thaw boundaries is purely segmental. Whether these segments have any particular significance or are merely fortuitous is difficult to conclude at this time. This is discussed further in Chapter VI - Conclusion.

In the comparison of soil distribution and freeze-thaw regionalization a similar problem exists. It appears impossible to incorporate a station-to-station analysis. But from simple inspection, boundary coincidences between freeze-thaw regions and major soil groupings such as those by Orvedal (25) or by Marbut (3) are limited to marked topographic relief and to the southern limit of the arctic. Since the impact of freeze-thaw phenomenon is principally mechanical, although there also exists the restraint on chemical decomposition, it may be possible to expand upon the concept expressed by Tsytovich and Sumgin (39). In their studies on frost phenomena, they maintain that silt particles are the end product of mechanical reduction by frost action in the arctic. They report that in a number of arctic locations, silts comprise 80 to 90 per cent of the soil. On the other hand, Penck (27) considers clay particles to be the end product of chemical weathering. Therefore, comparisons made by mechanical analyses along a north-south extent might indicate significant effects of freeze-thaw upon soil composition. Considering the many variables involved in soil formation, actual testing for any relationship between freeze-thaw and soil composition can be accomplished only by a rigid statistical analysis perhaps necessitating machine tabulation. Consequently, the following short discussion on possible relationships between freeze-thaw and soil distributions serves more to illustrate the character of the problem than to obtain definitive results.

The mechanical analyses given below were obtained from Baker (3) and represent a north-south extent from Krydor, Sask., to Amarillo, Tex. These analyses are for the first 5 inches of soil depth and all stations are classified as Chernozems. As can be seen

Table I. Mechanical Analysis of Soils over a North-South Extent

Station	Sand				Silt	Clay
	Coarse	Medium	Fine	Very fine		
Krydor, Sask.	3.2	2.5	12.2	10.1	58.4	12.9
Mandan, N.D.	0.9	0.8	8.4	24.2	54.9	10.3
Holdrege, Neb.	0.2	0.1	0.5	8.5	65.0	25.6
Jetmore, Kan.	0.0	0.3	2.0	19.5	52.1	26.3
Amarillo, Tex.	0.2	0.3	2.6	12.1	55.1	27.6

from Table I, the percentage of clay increases southward, but the percentage of silt present remains essentially the same. It is probable that decomposition is more complete in the south, but no conclusive evidence is to be drawn from Table I. Only a thorough statistical analysis could produce a reliable answer. As with vegetation, further discussion is included in Chapter VI - Conclusion.

CHAPTER VI

CONCLUSION

Theoretically, the phenomenon of freeze-thaw has qualities for being unique and critical within the complex of the natural environment. The phenomenon is a finite physical process involving the change of water from the liquid to the solid state and the reverse. During the process extraordinary forces become available because a density differential exists between the liquid and solid states. Furthermore, there are relatively large amounts of heat involved during these changes of state. Another factor is the physiological one of the availability or non-availability of water to sustain growth. But the coherent factor in terms of climate is the dependence of freeze-thaw upon a definite and measurable temperature threshold. It is upon these facts that the first part of the initial premise is made; that is, as to the criticalness of freeze-thaw phenomenon as a climatological parameter. Several features of the highland and arctic landscapes are attributed to the occurrence of alternating freezes and thaws by Flint, Pearsall, Benninghoff, and Troll. These features are most noticeable where erosion by running water is of minor importance. Toward the other end of the climatic spectrum are certain vegetation species such as citrus fruits, date palm and sugar cane whose tolerances to the onset of the freeze-thaw cycle are extremely low. Now it is reasonable to assume that the effect of alternating freezes and thaws is not limited only to the soils of highlands but that this phenomenon also contributes to soil development wherever freezes and thaws occur. It is reasonable to suspect, also, that all vegetation is affected by the occurrence of the phenomenon but that each species may be influenced to a different degree. Upon these reasonable assumptions the second part of the initial premise is based; that is, on the significance of freeze-thaw as a connecting link between climate as such and the landscape where the phenomenon occurs.

Accepting the validity of these basic assumptions, the logical approach for this study became the possible regionalization of the freeze-thaw phenomenon and the degree to which such regionalization is reflected in the distribution of accepted environmental factors such as precipitation, vegetation, and soils. With this approach, temperature records from 172 stations in the United States and Canada were processed for freeze-thaw data. These data were then put in diagrammatic form and mapped. As a result of the analysis, nineteen major freeze-thaw regions were delineated and of these, nine were further divided into subregions. Differentiation of the regions was based on readily apparent differences in characteristics and levels of freeze-thaw activity, and in no way were arbitrarily chosen levels introduced. The regionalization is considered to be orderly and logical. Therefore, the initial premise as to the criticalness of the freeze-thaw phenomenon as a climatological parameter is considered to be substantiated.

The degree to which freeze-thaw regionalization is reflected in the distributional patterns of accepted environmental factors of precipitation, vegetation and soils varies considerably. For precipitation, data from the same stations and the same period of record were also processed, put in diagrammatic form and mapped. From the data twenty-one major precipitation regions were delineated and of these only four were divided further into subregions. On comparing the freeze-thaw pattern with the precipitation pattern, it became evident that there exists a significant level of coincidence between several of the boundaries. The effect of topographic control is markedly shown by common boundaries along the crests of the northern Pacific coastal ranges and along the Rocky Mountain front of the western mountain and plateau complex. In the north, the areas commonly known as the arctic and subarctic are delineated very similarly by both patterns. The northeastern Atlantic coast of the United States and of Canada is another such boundary. Within the west central part of the continent, the two patterns practically coincide from Sioux Falls through Bismark and Fort Peck, to the mountains near Lethbridge. From Sioux Falls northward the boundaries of the two patterns diverge only slightly, whereas, from Sioux Falls southward, the precipitation data delineates a transitional zone through which extends the freeze-thaw boundary. Elsewhere, the boundaries of the two patterns can only be considered in generalities. However, the marked general agreement between the freeze-thaw and precipitation patterns lends support to the concept of freeze-thaw activity as a significant index to climate.

The degree to which the freeze-thaw pattern is reflected in the distributional patterns of both the natural vegetation and that of soils is rather low. In each case, the freeze-thaw pattern was compared with generally accepted classifications of natural vegetation and soils. Although there exists the possibility of not having used a sufficient number of stations, or the most representative stations to make such comparisons meaningful, it is doubtful that on the scale attempted in this study, the myriad and unknown factors could be delineated. On the other hand, on comparing the freeze-thaw pattern with geographical limits of individual crops and trees, several general coincidences of boundaries are apparent. Whether these coincidences are real or merely fortuitous would be difficult to prove at this time.

Superficially, the research does not appear, to fully meet the expectations implied in the initial premise of this study. On the other hand, to fully support the significance of accepted climatological factors may be equally as difficult. For example, a theoretical discussion on the attributes of precipitation which makes it a significant climatological element is rare if not absent. It would seem "Everyone is apparently aware of or knows that precipitation is significant". This is acceptable for precipitation per se but not as a parameter. Various precipitation levels, even those commonly used in geography, have no meaning within themselves or with each other. However, in terms of vegetation in particular areas, precipitation can become a parameter where certain levels are associated with vegetation differences. The difference between the short grass region and that of the tall grass within the plains area of the United States is an illustrative case. Often, the 16 or 17 inch isohyet is used in delineating the two regions. However, this precipitation boundary or any other is not effective in delineating short grass regions from tall grass regions on a universal basis. Nor is it universally possible to completely associate a type or species of vegetation to either end of the precipitation spectrum. This study has shown, however, the possibility of delineating natural precipitation regions based upon significant components of precipitation activity. Regionalization is possible without the necessity of relying on arbitrarily established limits. The regionalization established in this study follows an orderly and logical sequence. In terms of the freeze-thaw pattern there is a general level of significance; yet, in terms of vegetation and soils, there is hardly a slight coincidence on the scale attempted by this study. Certainly, the agreement is no better than that between the the freeze-thaw pattern and the distribution patterns of natural vegetation and of soils.

What pertains to precipitation also pertains to the phenomenon of freeze-thaw although with the latter, the theoretical premise is more easily stated in concise terms. In one particular case the effect of an occasional occurrence of the freeze-thaw cycle is well known and to those closely associated even the effects of different levels or degrees of severity and timing of the freeze-thaw activity are predictable. This situation exists, of course, in the citrus industry. At the other end of the activity spectrum is the situation in most highland areas. There the cumulative effect of the very high freeze-thaw activity is also known. Between the two extremes lies the greater bulk of area where freeze-thaw occurs. In terms of frequency, duration, and severity throughout the year, it is possible to regionalize the freeze-thaw activity without introducing artificial levels. The resulting delineation is orderly and logical in its sequence. But as in the case with the precipitation pattern, the degree of coincidence between freeze-thaw patterns and vegetation and soil patterns is rather low. It is concluded, then, that the degree of support for evaluating freeze-thaw phenomenon as a critical climatological parameter parallels and equals the support for the acceptance of precipitation as a critical climatological element. On this basis, it is considered that the significance of freeze-thaw is well substantiated. With respect to freeze-thaw as a connecting link between climate as such and the landscape where it occurs has been proved to be beyond the scope of this study. One promising feature, however, is the degree of agreement between freeze-thaw and precipitation patterns. Apparently, definitive relationships exist within the environment between orderly components which can be identified and mapped.

This could be the time to ask the difficult questions: "Why are relationships between climatic factors and between climate and the landscape so difficult to determine?" and "Why have results in the past been persistently unpromising and despite logical premises continue to remain so?" The natural landscape has frequently been used in the attempt to regionalize climate. More discriminating attempts propose the use of a single feature principally vegetation as the measuring stick. Unfortunately, this approach generally fails to reveal what mixing ratio or range of mixing ratios of the climatic elements is essential to the growth economy of vegetation. This is true whether it be vegetation per se or whether it is limited to a single species. When the relationship between an accepted vegetation classification and the delineated freeze-thaw patterns proved rather disappointing, relationships between individual species and freeze-thaw were sought.

In this respect, a very useful and informative article has been written by Hocker (11) in which he discusses his investigation of certain aspects of climate as related to the distribution of loblolly pine. This species, with the exception of the shortleaf pine, has the widest distribution of all southern pines. Its natural range sweeps from southern New Jersey to eastern Texas and from the Gulf into southern Arkansas and southern Tennessee. The climatic measurements Hocker uses are: (1) average monthly temperature; (2) average maximum and average minimum temperature; (3) average monthly precipitation; (4) average number of days per month with precipitation of 0.01 inch or more; (5) average number of days per month with precipitation of 0.50 inch or more; and (6) dates of the last frost in the spring and the first frost in the fall. On a seasonal basis, Hocker then had twenty-one variables which he subjects to statistical analysis using data for about two hundred stations; half of which are in the known range of the loblolly pine and half out. Of the twenty-one variables only twelve appeared significant, but the effects of the other variables could well have been absorbed by these twelve.

Hocker found that the calculated climatic limits followed rather closely the natural distributional limits of the loblolly pine. Which variable or variables were the most discriminating could only be surmised, although it is apparent that temperature is significant for determining the northern limits and precipitation the western boundary. It is interesting to note that much of the northern limit of the loblolly pine also follows the freeze-thaw division within the southeastern United States separating the region where freezes of two days duration occur from the region to the south where they seldom occur. The western limit, on the other hand, is approximated by the precipitation limit of this generally moist region.

Similarly, limits of the cultivated crops of cotton, spring wheat, flax, and timothy and clover, as given by Baker (2), also show some coincidence with the freeze-thaw patterns. The same may be said for the limits of several species of trees such as the tamarack, American sycamore, winged elm, and others, as shown by Little (21). But whether this is of significance or is purely fortuitous would be difficult to say or prove at this time. On the chance that the unusual might be the more significant, fall and spring months in which occasional freeze-thaw cycles could be expected were plotted but again the patterns are rather broad and show no particular promise. On the other hand, it seems impossible to ignore the occurrence of frost or conditions favorable to frost in the low-latitude lowlands. Krause (14) reports the occurrence of frost as early as May and as late as September in the northern Chaco of Paraguay. One station experienced 32° F or below 19 times in the period from 1940 to 1949. Also reported is an all-time low for the area of 19° F. This in a segment of an Aw (Tropical Wet and Dry) climate classification of Koppen's where the average temperature for the coolest month is 64.4° F or above. It may be that the occasional occurance of these low temperatures may not be critical to vegetation while it is dormant and in a state of dessication.

There have been no successful efforts, on a broad scale, to systematically incorporate other landscape characteristics into the regionalization of climate, such as flow, type, and density of the drainage, degree of slope and its orientation, grain of the topography and its elevation. Theoretically, all should be possible but it depends upon establishing a communications network between the climatic elements and the natural landscape which presupposes that there exists a measurable relationship. It has been demonstrated that it is possible to have measures of climate which in themselves differentiate one area from another, even though the measurements do not fulfill completely their initial promise. Climate and landscape are not two independent entities and this in itself should help to simplify the communication network between them. Considering the unpromising nature of past results and partially of the present results, the obvious question concerns the data being assembled and processed. Is it valid; completely so? For climate, the answer is only partially so and for landscape, incomplete. The greater concern here is for an adequate measure of climate.

The inadequacies of the regular reporting stations have long plagued the field of Ecology. On reporting their results of a well planned and executed program on the microclimate of a small Ohio valley, Wolfe, Wareham, and Scofield (42, p. 242) make the following comparison between the records obtained and the corresponding data of the combined network of reporting stations in Ohio.

"In Table 84 (see below) certain phenomena in the valley during 1942 are compared with the same phenomena over the whole of Ohio (43,000 sq. miles vs 150 acres). From these data it is evident that the variations in these phenomena are greater at Neotoma (valley) than they are in the published record of the whole network of 88 stations in Ohio."

"Table 84. - Comparisons of certain weather phenomena in the whole Ohio area with those at Neotoma in 1942.

Weather phenomenon (1942)	For Ohio	Neotoma
Length of frost-free period (days)	138-197	124-276
Date of last killing frost in spring	4/11-5/11	3/9-5/24
Date of first killing frost in fall	9/25-10/28	9/25-11/29
Annual maximum temperature (°F)	91-102	76-113
Date of maximum temperature	7/17-7/19	4/24-9/19
Annual minimum temperature	-5 to -21	14 to -25
Range of maximum temperatures (°F)	11	37
Range of minimum temperatures (°F)	10	39 "

Most studies of microclimate and of topographic climate make corroborative statements. Faced with such difficulties, it is not at all surprising that attempts to associate climate and the landscape end on such an unpromising note. If the associations between climate and the landscape are to be explored, then it becomes imperative to measure climate in the natural mantle of the terrain; certainly, not in the fastidious detail of microclimate nor in the obliterating effects of a standard exposure but more on the scale of topoclimatology. The limitations of the present network of reporting stations are rather well known. Stated simply - these stations measure an artificially established abstract of the landscape climate and there is no simple formula for associating the two. Certainly, the representativeness of the standard exposure varies between deserts, mountain highlands, short grass or forested sites. Topography and slope orientation add their indigenous problems. It is inconceivable to attempt the measurement of all variations possible within the climatic landscape. But a planned network of stations sited to reflect the surrounding landscape, and satellite stations established to reflect the variability within that landscape are well within the combined capabilities of the Weather Bureau, Agricultural stations, and interested Universities. The Weather Bureau has cooperative observers numbering in the thousands. Would it not be possible to re-evaluate their efforts and perhaps direct some of these efforts toward the greater need?

Climatic-landscape associations are only secondary end products in the field of climatology. The core remains the essence of climate as it is. Without such a goal, climatology can never attain the status of a science among its sister sciences studying the physics of the earth. Toward this goal, the climatologist may desire to initiate new instrumentation for the measurement of the atmospheric phenomena. And, perhaps, too, initiate a network of stations for reporting conditions at the air-landscape interface. With proper planning and instrumentation, there is no reason why the climatologist should not be in a position to contribute to the understanding of the physics of climate, and with the geographer, successfully explore the relationships between climate as such and the natural landscape.

In retrospect, this study shows that it is possible by considering the pertinent components of a climatic factor to portray the yearly distribution of that factor succinctly and simply. It further shows that this factor can be expected to vary in an orderly and logical sequence from place to place. In terms of freeze-thaw and precipitation the study finds a significant degree of coincidence between their respective orderly distribution patterns. It is therefore apparent that definitive relationships exist in the natural environment, but that these relationships will be revealed only through a thorough program of research in the field of climatology and in its related field of geography.

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FREEZE-THAW PHENOMENON AS A CLIMATOLOGICAL PARAMETER

Abstract

One of the more powerful and consistent tools available to nature is the phenomenon of alternate freezing and thawing. Mechanically, extraordinary pressures may be involved because of the density differential existing between the liquid and the solid phases of water. Physiologically, there is the availability or non-availability of water to sustain growth. Despite this, catastrophic changes are not to be expected. On the other hand, such a powerful tool must leave its imprint in one manner or another upon the natural landscape. In most arctic and highland areas the imprint is directly discernible. In more moderate climes the imprint is indirectly applied principally as a limiting parameter within an aggregate of generally favorable conditions.

The phenomenon of freeze-thaw is a climatic parameter but not a climatic element. Unlike the elements, there is a definite threshold involved; that is, 32° Fahrenheit or 0° Centigrade. At this threshold water may exist in either the liquid or solid state but by the addition or subtraction of heat it can change from one state to the other without a gain or loss in temperature. In the natural environment the terms are not quite so precise. Time for the process to take place, impurities in the water, and the variation of temperature regimes among the many nooks and crannies of the landscape point to the necessity of relaxing the temperature threshold. In this study the zone of 34° F and 28° F is used. Conditions favorable for

a thaw are thought to occur when the temperature rises through the zone and conditions favorable for a freeze when the temperature drops through this zone.

In several respects, the areal pattern of the freeze-thaw phenomenon is predictable, for it will reflect to some extent the known temperature regimes at particular locations. Such factors as marine exposures, continentality, highland areas, and latitudinal differences do affect the areal pattern. It is principally the question of relative definitiveness that is involved. This study develops the premise of the criticalness of the freeze-thaw process as a climatological parameter; plots the frequency, duration, and severity of the cycles in Anglo America, discusses the resulting orderly geographic patterns, and compares these geographic patterns with geographic distributions of accepted environmental features.

This study proves that by considering the pertinent components of a climatic factor, it is possible to portray the yearly distribution of that factor succinctly and simply. It further shows that the factor can be expected to vary in an orderly and logical sequence from place to place. In terms of freeze-thaw and precipitation a significant level of agreement is evidenced between the respective developed patterns. Therefore, it is apparent that definitive relationships do exist in the natural environment, but it is believed, however, that the extent of these relationships can be revealed only through a thorough program of research in the field of climatology and in its related field of geography.