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REGIONALIZATION OF FREEZE–THAW ACTIVITY

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THE process of alternate freezing and thawing has long been recognized as a subject of interest. In most periglacial and many extraglacial landscapes the direct effects of the activity are in ample evidence.[1] Even though the effects may not be directly apparent, it is generally accepted that alternate freezing and thawing contribute to the evolvement of the landscape wherever the process occurs with some frequency. Whereas studies have been made of the frequency of freeze–thaw, seemingly little attention has been focused on the inferences which might be drawn from an analysis of the activity on a regional basis.

The freeze–thaw process is unique and critical within the complex of the natural environment. The characteristic of increased volume in the change from liquid to solid state provides nature with a very powerful tool. Even to depress the freezing point of water by 5 or 6 F. degrees requires several hundred atmospheres of pressure. Under the most favorable conditions, pressures of over 2,000 atmospheres become available.[2] This wedging action is perhaps the major tool available for the mechanical reduction of rocks and rock fragments, and it is apparently capable of displacing even very large stone blocks.[3] Furthermore, frost in the ground inhibits percolation of meltwater or of precipitation into the ground, thereby contributing to possible flood conditions during late winter or early spring thaws. Whereas selective injury to vegetation by a sudden frost is often in evidence, a winter thaw can also create conditions injurious to vegetation.[4] However, in terms of climate, the coherent factor of freeze–thaw is its association with a temperature threshold. The frequency with which the temperature fluctuates through this threshold as well as the duration and departure from the threshold varies considerably from region to region. In tropical highlands the frequency of freezes may be very high,[5] although durations are short and severity light. In arctic areas the frequency of temperature fluctuations through the threshold are fewer but the durations below the threshold are much longer and the departures below are large. Here the number, duration, and extent of thaws become important. Conditions in the mid-latitudes are extremely variable. To what extent the distribution of freeze–thaw activity can be developed to provide climatic differentiation is a germane problem.

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[1] Of the following reference Flint presents in Chapter 11 a general discussion of frozen-ground phenomena; Troll describes the differentiation in soil structure and patterned ground in different areas of the world in relation to the frequency of alternate freezing and thawing cycles; Pearsall, in pp. 24–30, presents a succinct discussion of the freeze–thaw process in the evolvement of the highland landscape in the British Isles; and Benninghoff and Sigafoos each emphasize the importance of frost action in the soil as a control in the development of plant communities in the arctic. R. F. Flint, *Glacial and Pleistocene Geology* (New York: John Wiley and Sons, Inc., 1957); C. Troll, "Strukturboden, Solifluktion, und Frostklimate der Erde," *Diluvial-Geologie und Klima, Geologische Rundschau*, Vol. 34 (1944), pp. 545–694 (Translation 43, U.S. Army Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, Wilmette, Illinois, October, 1958); W. H. Pearsall, *Mountains and Moorlands* (London: Collins, 1950); W. S. Benninghoff, "Interaction of Vegetation and Soil Frost Phenomena," *Arctic*, Vol. 5 (March, 1952), pp. 34–44; R. S. Sigafoos, "Frost Action as a Primary Physical Factor in Tundra Plant Communities," *Ecology*, Vol. 33 (October, 1952), pp. 480–87.

[2] Water freezing in a closed vessel exerts a maximum pressure of 2,050 atmospheres at –22°C. (–7.6°F.). At lower temperatures the ice changes phase and contracts as it solidifies. See reference to P. W. Bridgman's investigations, p. 40, Walther Penck, *Morphological Analysis of Land Forms*, trans. Hella Czech. and Katharine C. Boswell (London: Macmillan and Co., 1953).

[3] Flint, *op. cit.*, pp. 196–97.

[4] L. B. MacHattie, "Red Belt Winter Injury of Lodgepole Pine Foliage." Paper given at the Second National Conference on Agricultural Meteorology, New Haven, October 22–24, 1958.

[5] Troll, *op. cit.*, p. 14. Figure 4 shows a frequency of 350–365 days of the year at elevations from 14,000 to 19,000 feet in the southern Peruvian Andes.

The purpose of this study is to analyze freeze–thaw activity on a regional basis and to compare the regionalization with distribution patterns of other environmental factors. For this study a diagrammatic form is devised for showing the average monthly frequency, duration, and severity of periods of freezing and thawing weather. From the diagrams a regional analysis of most of North America is developed. This analysis is compared with distribution patterns of precipitation, vegetation, and soils. If associations can be shown and are proven real, and not merely fortuitous, then the distribution of freeze–thaw activity warrants consideration as an additional tool for climatic analysis.

TEMPERATURE THRESHOLD FOR FREEZE–THAW

The freeze–thaw phenomenon has a uniqueness not often found in nature, that is, sharpness in a discrete change of phase occurring under natural conditions. Because of the relatively high latent heat of fusion of water, there is a marked temperature stability within the ice–water mixture. This can be significant within the heat balance of the microenvironment. Longley detected the effect on the temperature curve at Quebec City, Quebec.[6] However, as there is no detailed network of direct measurements of freeze–thaw in the environment, measures of such a factor must at present be induced within the limits of available data and the objectives of a particular study.

Shelter temperatures of 31°F. and 33°F. were used by Alpert for determining the number of times buildings within a city are exposed to freeze–thaw conditions.[7] Each drop to 31°F., or below, followed by a rise to 33°F., or above, was considered as a single alternation between an effective freeze and thaw. By counting the number of such cycles he was able, within the objectives of his study, to determine yearly frequency of freeze–thaw from the daily maximum and minimum temperatures recorded at the cities studied. In a more comprehensive study, Russell used the temperatures of 28°F. and 32°F. for determining effective freeze–thaw cycles.[8] Almost ten million individual maximum and minimum temperatures recorded at 863 cooperative Weather Bureau stations were used for compiling a map showing yearly distribution of freeze–thaw cycles occurring in the United States.

Although Russell did not state them, he implied the effects of both mechanical and physiological stresses by using such terms as effective for freeze–thaw at ground surface and killing frost with respect to vegetation. There existed the problem of establishing the meaning of effective within the scope and objective of his study. The concern was with conditions in the natural environment. For better geographic coverage, and for better representation of the natural environment, Russell preferred cooperative station records, although these limited the temperature data to daily maximum and minimum readings. This precluded direct use of a duration factor. But, as he stated, under ordinary conditions a short drop to 28°F. as recorded in the instrument shelter constitutes a killing frost and, furthermore, such a temperature at five feet above the ground would also under normal conditions insure an effective freeze at ground surface. Principally upon this and upon suitability of the data to the study, Russell established the level of 28°F. as evidence of an effective freeze. On the other hand, the 32°F. level as evidence of an effective thaw was based on the premise that, with rising temperatures, when 32°F. is reached in the instrument shelter the ground would under normal conditions be considerably warmer. With regard to freezing conditions, the reasonable assumption was made that the number of cases where effective freezes do not occur at the 28°F. level would be more than offset by the number of cases where effective freezes do occur within the 28–32-degree level because of longer exposures. Therefore, in computing yearly frequency of freeze–thaw,

[6] R. W. Longley, "The Effects of Freezing and Melting Processes on the Daily Temperature Curve at Quebec City," *Quarterly Journal, Royal Meteorological Society*, Vol. 75 (1949), pp. 268–74.

[7] Leo Alpert determined the frequency of freezing and thawing cycles for twenty-four cities in the United States. See Structural Clay Products Institute, "Adhesion Type Ceramic Veneer," *Technical Notes on Brick and Tile Construction*, Vol. 4 (May, 1953).

[8] R. J. Russell, "Freeze-Thaw Frequencies in the United States," *Transactions, American Geophysical Union* (1943), pp. 125–33.

Russell considered it sufficient to count each temperature drop to 28°F. or lower followed by a rise to 32°F. as a single alternation between effective freeze and thaw.[9]

In contrast with the above two studies, the discussion that follows 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 to some degree be a measure of climate; and because of mechanical and physiological factors involved, the process may, furthermore, leave a recognizable or associable imprint upon the natural landscape. This new study is an analysis of relative differences or similarities of freeze–thaw activity from station to station over Canada and mainland United States. Thus it is concerned primarily with a reasonable and acceptable base upon which to make such comparisons. Basic data are, of course, the same as available to Alpert and Russell. But as Russell pointed out, temperature data on an extensive areal basis are available only from climatological records obtained within well-ventilated shelters exposed to free movement of air.[10] But within the quite limited vertical zone encompassed by the natural landscape, it is frequently not the question of 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 subject to discussion;[11] therefore, it is quite likely that the question of representativeness of temperature data could well place a limit on the degree to which a study of freeze–thaw activity may be pursued and in what detail. Nevertheless, for the limited objectives of this investigation, representativeness of shelter temperatures poses no serious problem.

A difference of two or three degrees can be expected among daily maximum or minimum shelter temperatures even in relatively homogeneous areas when the unifying factors of cloud cover, precipitation, or fog do not occur. Differences near ground level are even greater. It is readily appreciated that any establishment of temperature levels for freeze–thaw with the implication of their effectiveness is rather subjective on the basis of readily available temperature data. For this study the levels of 28°F. and 34°F. are used. That is, when the temperature drops from 34°F. to 28°F. or below, conditions are considered conducive to the freezing of water in the natural environment. Conversely, when the temperature rises from 28°F. to 34°F. or above, conditions are considered conducive to melting frozen water. One other factor taken into account in selecting the freezing level is that a level two degrees lower than the selected value materially affects the freeze–thaw patterns for certain stations, particularly those experiencing mild climates of the West Coast and of the Gulf states. It should be remembered that this study is an analysis of the relative differences or similarities of freeze–thaw among the individual stations. The temperature levels of 28°F. and 34°F. appear best to satisfy the broad areal requirements and yet appear stringent enough to warrant the implication effective.

However, it is also possible to join Alpert and Russell in stating that if, through experience, the temperature thresholds need modification, the principal change would be with relative numbers and not the relative patterns of freeze–thaw activity.

GRAPHIC PRESENTATION OF FREEZE–THAW DATA

Sources for maximum and minimum temperature records 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, geographic coverage is complete. Cooperative observers are located in many remote places and their records fill an otherwise barren area. Agricultural stations, too, are often located in sparsely settled areas. As more in keeping with the landscape, these records are preferred for a study of this type.

[9] Russell, *op. cit.*, pp. 126–27.

[10] *Ibid.*

[11] For example, during 1942 a greater variation in temperature regimes was found within the microclimates of Neotoma Valley (150 acres) than was shown in the published records of the network of 88 stations in Ohio (43,000 sq. miles). See J. N. Wolfe, R. T. Wareham, and H. T. Scofield, *Microclimates and Macroclimates of Neotoma, a Small Valley in Central Ohio* (Columbus: Ohio Biological Survey Bulletin 41, Ohio State University, 1949), pp. 239–43.

However, most meteorological networks are comprised of airport and city stations and, of the two, the airport station records are preferred.

For many stations Russell found a three-year record sufficient to arrive at a stable freeze–thaw frequency for the year.[12] Even for those stations with a history of erratic temperature regimes, he found little change in cumulative averages when data beyond that of the sixth year were employed. This length of record is far less than that advocated by Landsberg and Jacobs for establishing a stable yearly frequency distribution for temperature.[13] For extratropical regions they recommend ten years of data for island stations, fifteen years for stations near the shore, fifteen years for plains areas, and twenty-five years for mountain locations. It would appear that the freeze–thaw zone is a more conservative factor than the element from which it is derived. The limiting factor in this study is not the stability of the yearly frequency, but the degree by which freezes or thaws dominate during any particular month. At a number of stations the average temperature regime during a particular month over the years has sufficient range around the 28- to 34-degree zone so that for some years fluctuations through the freeze–thaw zone should be considered as a series of freezes and in other years as a series of thaws. This alternation is generally a distinctive feature in the freeze–thaw pattern for the station, and is an element of variability usually well established by processing seven years of data. The work of processing additional data does not seem commensurate with the slight additional level of definitiveness. For most stations, therefore, seven years of record are processed for the needed freeze–thaw data. A few stations in more remote reaches of Canada, with only four or five years of data available, are used when desirable geographic coverage is needed.

In processing and presenting freeze–thaw data, Alpert's purpose would be served by counting the freeze–thaw alternations and giving the average yearly total for individual cities by means of a table. Russell also used tables for discussing point to point differences of yearly frequencies, but the main body of his data was presented in map form by using isopleths. In this presentation Russell was confronted with a spread of 0 to 188 cycles per year, which he partially solved by using a progressive series of fractional parts of the year, beginning with ½ because the highest frequency approximates half the number of days in the year, and progressing through ¼ and so forth. The result was not completely satisfactory because of the very close spacing of isopleths in the west coastal areas and lack of differentiation in the Mississippi drainage basin and the plateau and mountain region of the west. The latter situation was remedied by incorporating an extra isopleth in each of these regions.[14] However well the resulting map shows areal distribution of the yearly frequency, it also shows that arbitrary divisions of freeze–thaw activity are in themselves of little value. It is obvious that something more detailed than yearly frequencies is needed. In the study presented below, data are compiled on a monthly basis to provide duration, severity, and frequency of freeze–thaw, as well as to determine whether the activtiy during the months is to be identified as a series of freezes or thaws. It should be significant in determining whether freezes or thaws are limited to one or two days, or whether durations of three, four, or more days occur. Relative severity of the activity (that is, minimum temperatures associated with freezes and maximums with thaws) may also provide a significant guide to permit discrete comparisons between stations. For simplicity and facility in making comparisons, monthly averages are incorporated into each station diagram for the factors of frequency, duration, severity, and determination as to whether freezes or thaws. The diagrams have greatly aided interpretation of the data with respect to differentiation from station to station.

From daily maximum and minimum readings at a station, the following items of information are available: 1) frequency, or actual number of cycles per month; 2) duration in days for each freeze or thaw; 3) severity of

[12] Russell, *op. cit.*, see Table 2, p. 128.

[13] H. E. Landsberg and W. C. Jacobs, "Applied Climatology," *Compendium of Meteorology*, Thomas F. Malone (Ed.) (Boston: American Meteorological Society, 1951), pp. 976–92.

[14] Russell, *op. cit.*, pp. 129–30.

the freezes or thaws; and 4) nature of the temperature cycles, whether freezes or thaws. In processing the data, the initial step is a check on the monthly averages of the maximums and the minimums to determine whether fluctuations are to be considered in terms of freezes or thaws. When the average minimum temperature is 34°F. or above, then any temperature fluctuation to 28°F. or below is considered a freeze. Similarly, when the average maximum temperature is 28°F. or below, a fluctuation to 34°F. or above is treated as a thaw. Frequently, however, this is determined by the relative differences between average monthly maximum temperature and 34°F., on the one hand, and average monthly minimum temperature from 28°F., on the other. When the former is greater, fluctuations are considered as a series of freezes; when the latter is greater, they are treated as a series of thaws. When the identity of the series is not immediately apparent, the sum of individual departures of maximums above 34°F. is compared with the sum of individual departures of minimums below 28°F. Again, if the former is larger, the fluctuations are considered as a series of freezes; and if the latter is larger, then as a series of thaws. Durations of freezes are determined by the number of days which the temperatures remain below 34°F. after the initial drop to 28°F. and durations of thaws by the number of days the temperature remained above 28°F. after the initial rise to 34°F. Severity of the freeze or thaw is determined by the departure from 28°F. or 34°F., as the case may be. Monthly average is obtained by dividing the sum of departures by the appropriate number of days when either freezes or thaws occur. Figure 1 shows how this information may be presented by graphic means.

The base line in Figure 1 extends from July through December (D), January (J), and June. The purpose of this arrangement is to effect continuity in the monthly presentation of data, since in most areas activity is continuous from autumn through spring. Differentiation between freezes and thaws is obtained by plotting frequency of thaws above the base line and of freezes below the line. 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 temperature variability inherent in the climate. For example, in Figure 1, March and November show this variability. In this case, position of the column simply means that the average temperature during these months is close to the critical zone of 28° to 34°F.; for some years the average will be above and for 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 lengths of the divisions. The first clear space from the base line is an indicator for cycles completed within twenty-four hours; the first solid bar for durations of two days; the following clear space for three-day periods and the second bar for four-day periods. Longer durations are experienced but these are averaged out in the processing. 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 numbers inserted beneath the base of the station model is the average number of freeze–thaw cycles for the year, and the lower number is the station elevation in feet.

Data presented in the diagrammatic form of Figure 1 are compact and are more readily assimilated for comparison purposes when a large number of stations is involved than the same data presented by individual charts or tables. Interpretation to a certain extent remains subjective, but as the station model contains practically all the pertinent data, the basis for the subjective selection is evident.

INITIAL SAMPLING OF TEMPERATURE LEVELS AND PRESENTATION OF INFORMATION

An east–west sampling across southern Canada and northern United States, from the Atlantic to the Pacific Ocean, was made as an initial test as to suitability of selected temperature levels and also as an evaluation of the diagram's adequacy for presenting information. The sampling area is represented by diverse topography where a relatively high contrast in freeze–thaw activity could be expected. Stations used are considered representative of Pacific maritime conditions, western mountain regions, Great Plains, Great Lakes area, eastern highlands, and the eastern

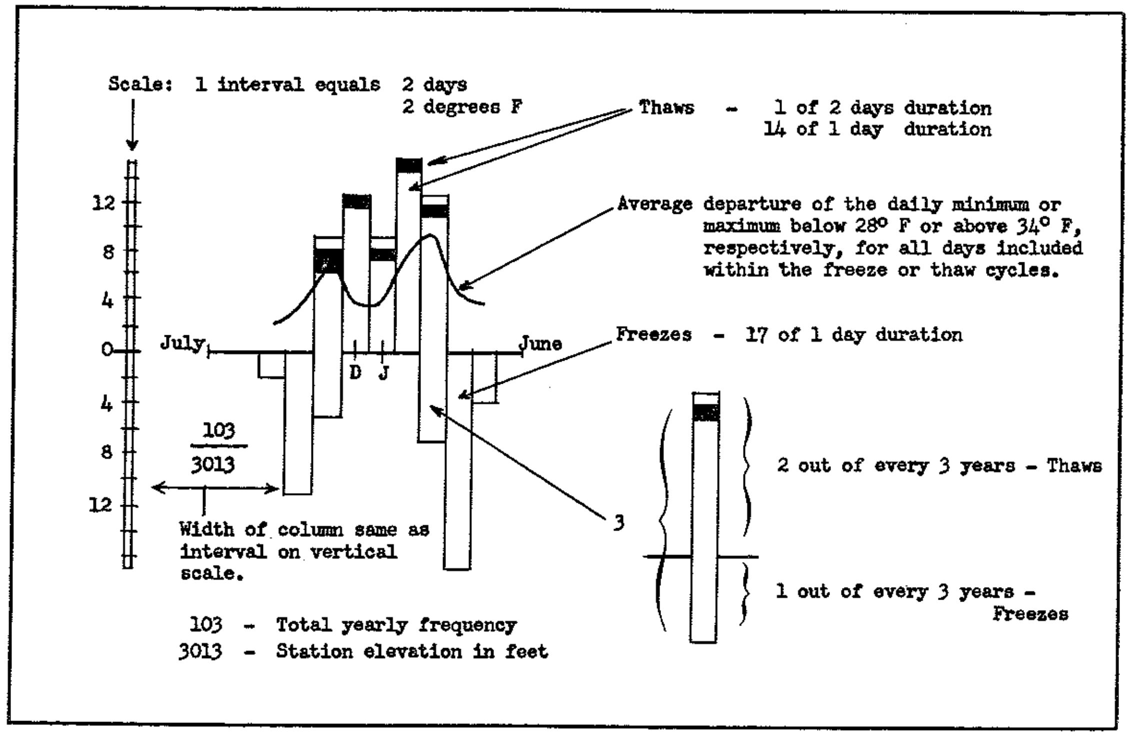

FIG. 1. The freeze–thaw diagram.

Figure 1 is based on data for Cranbrook, B.C., a station located in a high, narrow valley. The yearly frequency of 103 cycles is consistent with what would be expected from its site and elevation of 3,013 feet. Initial activity in the autumn is light: only two freezes are expected in September with temperatures dipping to around 26°F. and rising 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. November shows the occurrence of both freezes and thaws. By estimating the length of the column below the base line to the total length of the column, an approximation can be made 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 six degrees above the temperature level of 34°F. for the thaws and below 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 whereas during the other two years activity will be in terms of thaws. April shows a rather high (17) frequency of freezes, although these are limited to one-day durations. The activity extends into June with about four freezes to be expected. The station has only June, July, and August in which the temperature will remain above the lower critical level.

maritime exposures. In all, data for twenty-eight stations were processed using three different, although overlapping, temperature zones. These were: 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., as this latter figure is frequently considered critical to fruit trees and vegetables. As suspected, resulting freeze–thaw patterns were essentially alike. However, differentiation or similarity existing between stations is clearly in evidence from the diagrams.

In terms of yearly frequency of freeze–thaw cycles there is little difference in the use of 34°F. or of 32°F. as the upper limit, but there is a marked difference in the use of 28°F. or of 26°F. as the lower limit. Yearly frequency at Portland, Oregon, drops from 15, using 28°F., to 11 with 26°F. as the lower limit; at Cranbrook, B.C., the drop in fre-

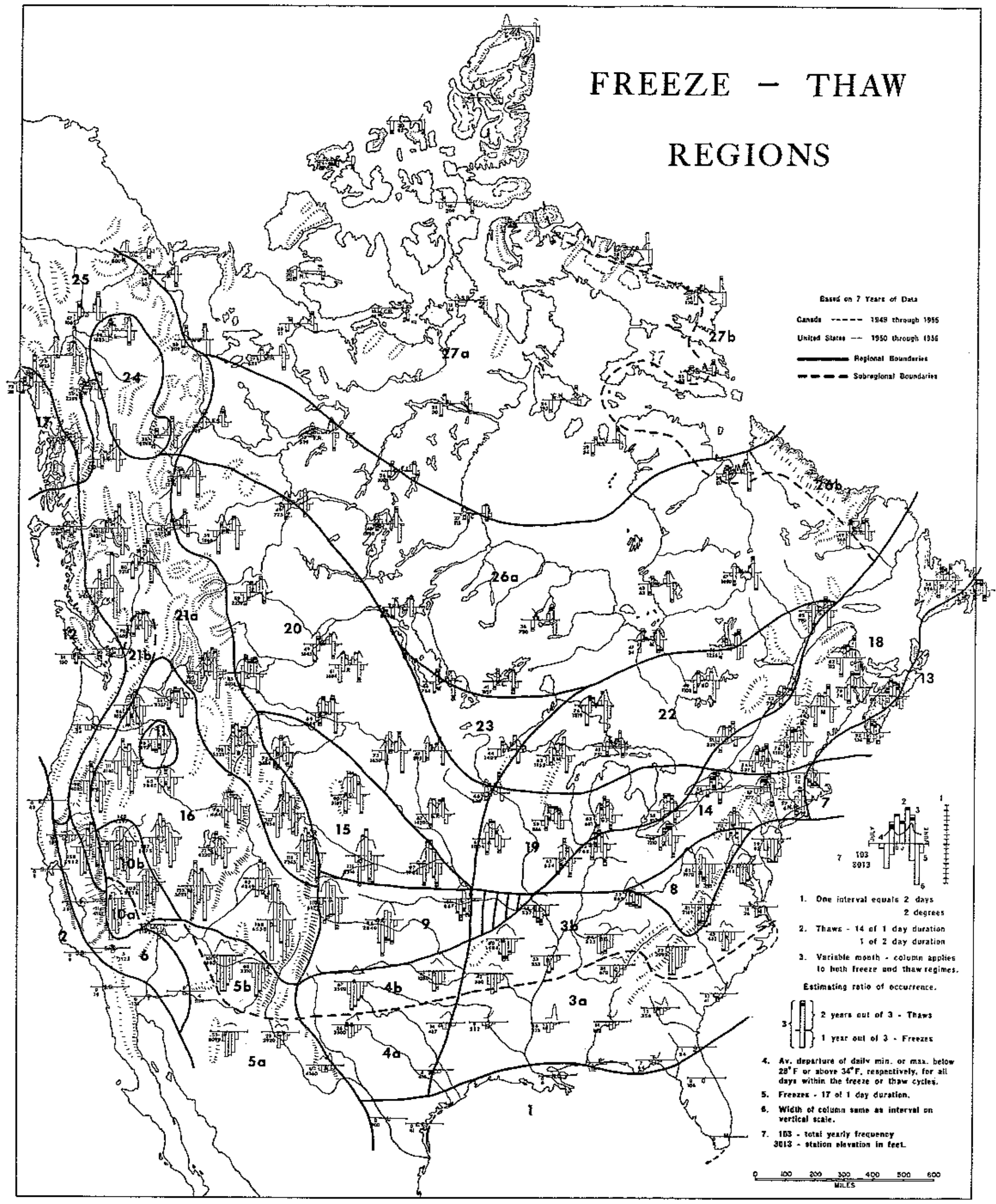

FIG. 2. Regions based on frequency, duration, and severity of freeze–thaw activity.

quency is from 103 to 89 a year; at Bismarck, N.D., it is 73 to 65; and at Yarmouth, N.S., the change is from 52 cycles per year to 46. The principal change is in the number of freezes recorded, whereas in the overall pattern it affected only one station, Bismarck, N.D., and that only slightly. The difference between 32°F. and 34°F. appears principally in the slight reduction in durations of the thaw periods which, again, is not significant to the overall pattern. It is evident that Russell's criteria could have been used in this

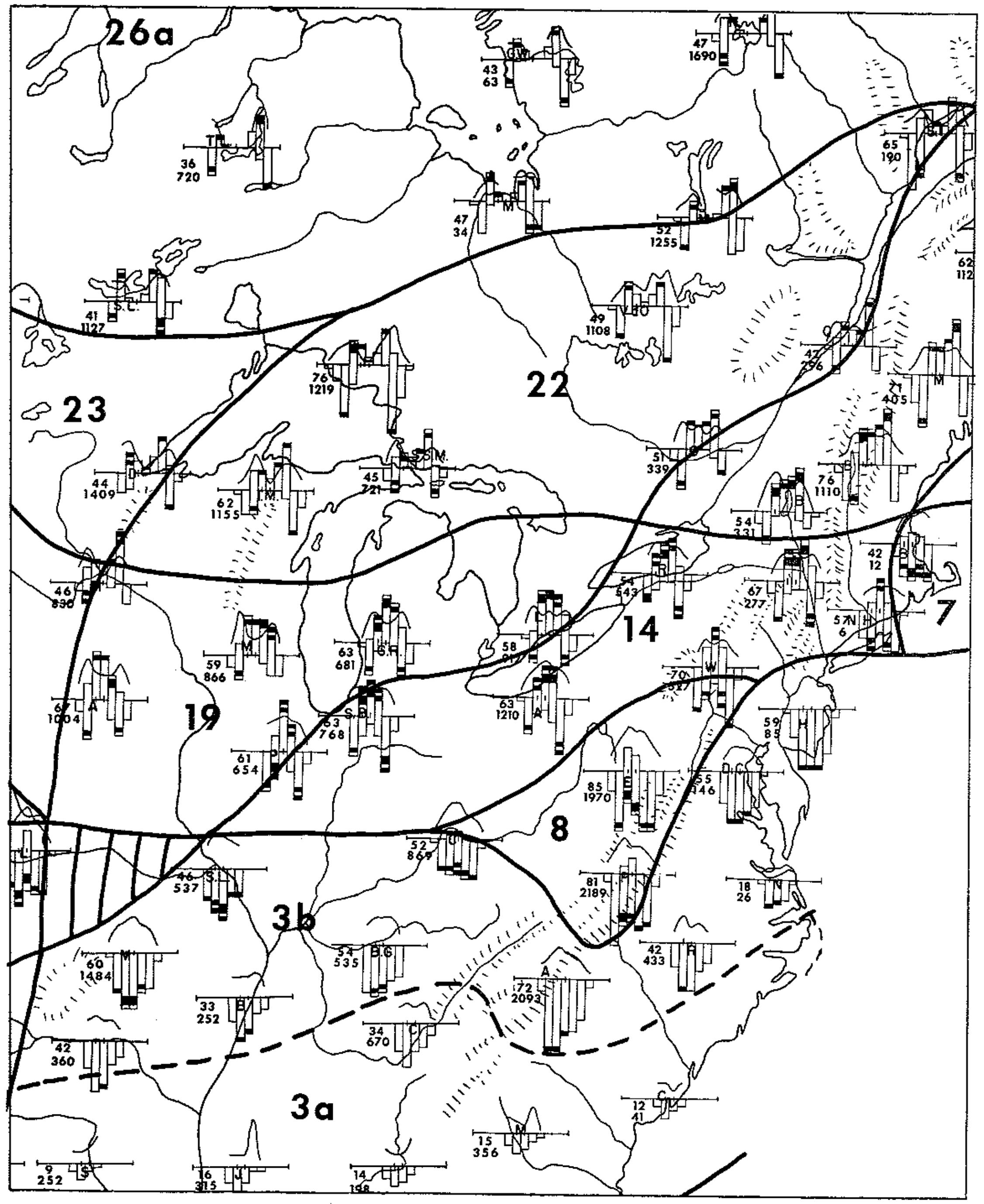

FIG. 3. Freeze–thaw regions of east-central North America; the section is an enlargement from Figure 2.

study. It is even possible that the temperature levels of 36°F. and 26°F. could be adopted, but they appear to be on the outer fringe of practicability. For this study the preference is given to 34°F. as the upper limit and, in agreement with Russell, 28°F. as the lower limit.

The sampling was intended to explore the more pronounced changes occurring between commonly understood geographic areas rather

than to make the actual differentiation itself. In all, the profile across the continent supports the major premise as to the expressiveness of the freeze–thaw process as an environmental factor in climatology in that, at least, it is reflected by distinct geographical areas. In addition, differences and similarities are readily revealed by the station diagrams. It remains to be seen how much areal differentiation is possible over a region that extends a great distance from north to south.

FREEZE–THAW REGIONS

Areal limits of the present study extend from Alert (82°30′ N.) in the Northwest Territories of Canada to Corpus Christi (27°46′ N.) in Texas and Miami (25°49′ N.) in Florida. East–west extent continues from ocean to ocean. In all, temperature records for 96 United States stations, 74 Canadian stations, and 2 Alaskan stations are analyzed for frequency, duration, and severity of freeze–thaw activity. The two Alaskan stations are on the lower Pacific Coast and serve to complement the Canadian stations. The number of stations is considered sufficient to provide adequate geographic coverage.

The diagrams place a limitation on the number of stations that may be incorporated on a small scale map; nevertheless, 172 diagrams are represented on Figure 2. Figure 3 presents an enlargement of most of the southeastern quadrant of Figure 2; and one station diagram from each region is reproduced by Figures 4 and 5 as an example of freeze–thaw conditions in the respective regions. At page size, Figure 2 provides only bare threshold legibility for the diagrams; however, the reduction makes it possible to present several station diagrams for each of the major regions subsequently delineated. Furthermore, on a corresponding scale, the possible related features of terrain, vegetation, and climate are most readily available for purposes of comparison.

The variations between widely separated stations, and between stations of marked elevation differences, are readily ascertainable from Figure 2. But actual placement of boundary lines depends upon a finer degree of differentiation. The freeze–thaw pattern of a station is compared for overall similarity with the pattern of the station just to the north, to the east, to the south, and to the west. Then details assume importance: 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 four days; 6) whether these durations are more frequent as freezes or as thaws; and 7) severity of the freezes or thaws and the monthly season of greatest severity.

During the analysis a degree of zonation, in terms of average monthly freeze–thaw activity, became apparent as the climate increased in severity from south to north and from the coastal areas inland. The zonation is helpful in grouping the various regions for discussion. However, boundaries thus delimited are, for the present, in no sense more valid or important than the criteria used in determining east–west divisions within the grouping, though the latter criteria are more varied and, perhaps, reflect the intricate complex of several factors. Since the map is prepared from data that are representative, strictly speaking, only for their own shelter temperatures, interpolation between stations is mainly subjective. Boundaries thus delimited may be moved slightly between stations and still satisfy the conditions for which they were drawn. By the analysis, twenty-seven regions have been delineated; and of these, six are further divided into sub-regions. Representative station diagrams for these regions and some of the sub-regions, arranged by groups, are given in Figures 4 and 5.

Group I: Regions 1 and 2

Region 1 extends over the coastal areas of the Gulf states and most of the peninsula of Florida. Region 2 is another coastal strip extending from Oregon to southern California and then inland and southward to the Yuma, Arizona, area. In these two regions freeze–thaw is not sufficiently frequent to show up in the monthly averages. This does not imply that freezes do not occur in the two regions or that they may not be severe enough to influence the landscape. Occurrence of the occasional freeze which creates havoc with specialized crops in these regions is well publicized. But at this stage further subdivision of the data does not appear warranted. During the period investigated, New Orleans, Louisiana, experi-

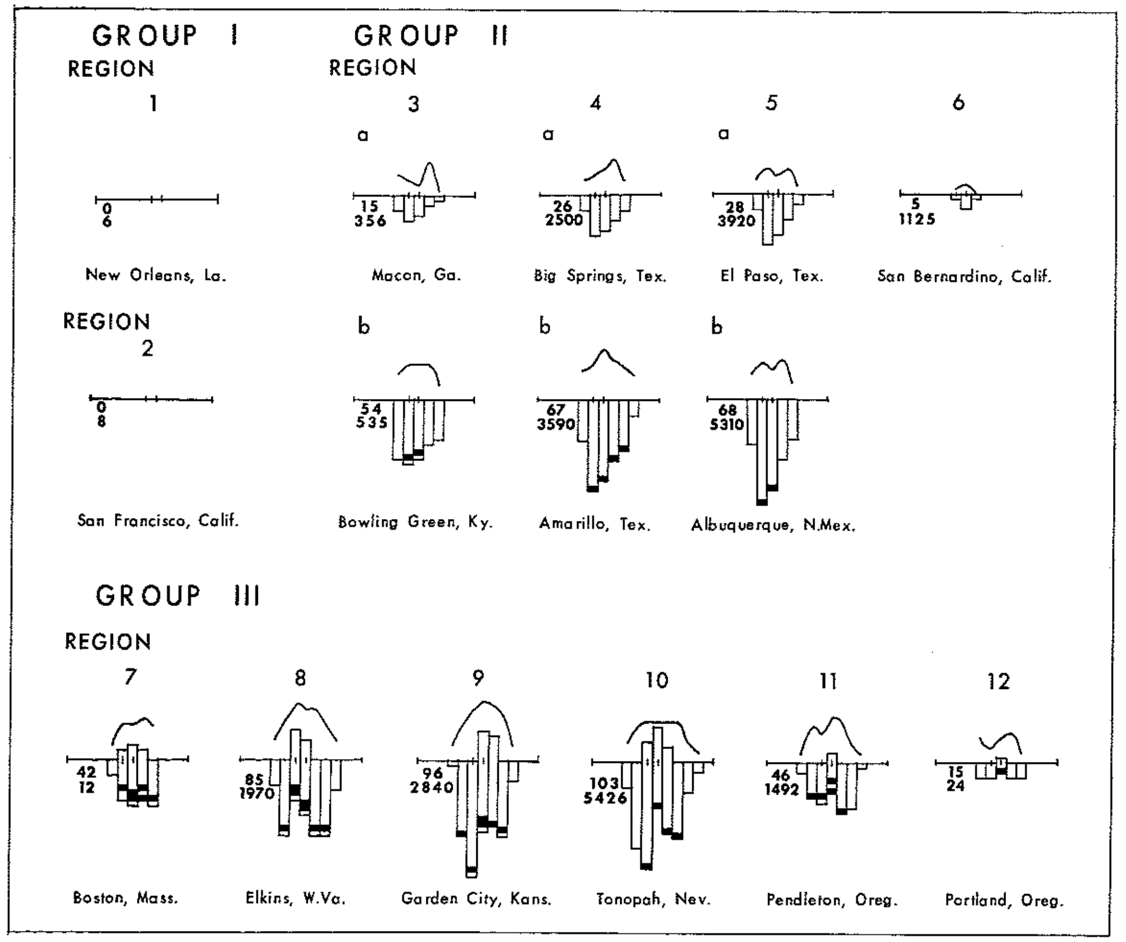

FIG. 4. Representative stations for Groups I, II, and III.

enced three freezes, one of which lasted two days; at San Francisco, California, only one freeze occurred. The freeze–thaw diagrams for the two stations showing only the base line, zero frequency, and the station elevation in feet are given under Group 1 in Figure 4.

Group II: Regions 3, 4, 5, and 6

The freeze–thaw characteristic of this grouping is that the activity can be regarded only in terms of a series of freezes. Regions 3, 4, and 5 are further subdivided into sub-regions *a* and *b*. Average duration of freezes in sub-region *a* is limited to one day whereas in sub-region *b* freezes of two or more days are quite frequent. Region 3 is comprised of the south-central and southeastern United States. Region 4 is the southern plains area of Oklahoma and Texas. Region 5 is the higher plateau areas of Arizona and New Mexico and also the far western strip of Texas. Region 6 encompasses the lower western part of Arizona, interior of southern California and the interior valley of the same state. Yearly averages in this group vary widely from 1 at Jacksonville, Florida, under the influence of warm tropical water to 101 at the high, dry plateau site of Winslow, Arizona. Effect of elevation on freeze–thaw activity is somewhat more apparent in this group of regions than in those of Group I.

Differentiation between Regions 3 and 4 is based on the temperature departure curve. In Region 3 the curves lack consistency and are either rounded, flattened, or irregular. In Region 4 the curve shows a sharp winter peak: in sub-region *a* the peak occurs in February while the sub-region *b* the peak occurs in January. The temperature departure curve also differentiates between the freeze–thaw activity of Regions 4 and 5. In Region 5 the January dip in the curve is characteristic in contrast to the peak in Region 4. Activity in Region 6 is quite limited and is in marked contrast to the activity at higher elevations to the east and northeast.

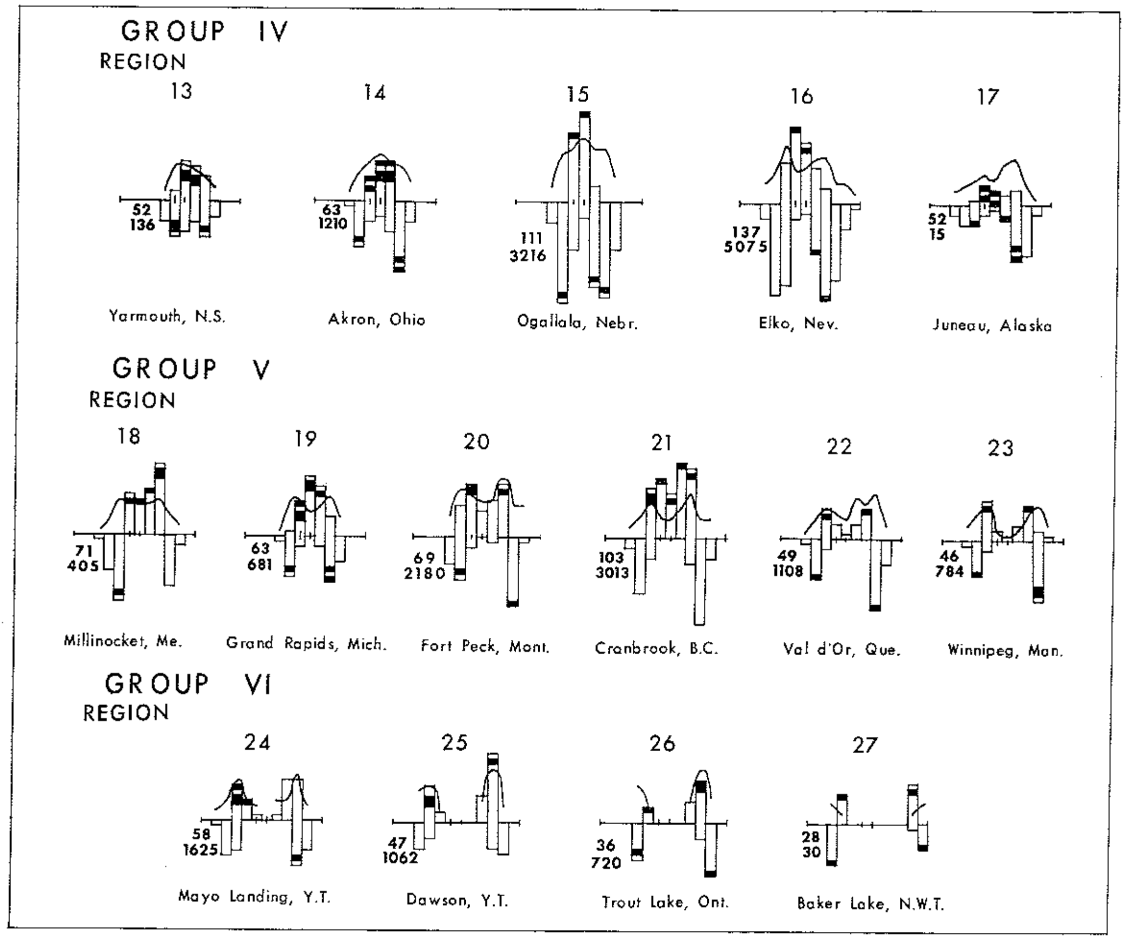

FIG. 5. Representative stations for Groups IV, V, and VI.

Representative stations for these regions are: Region 3*a*, Macon, Georgia; 3*b*, Bowling Green, Kentucky; 4*a*, Big Spring, Texas; 4*b*, Amarillo, Texas; 5*a*, El Paso, Texas; 5*b*, Albuquerque, New Mexico; and for Region 6, San Bernardino, California. All activity is shown as a series of freezes below the base line.

Group III: Regions 7, 8, 9, 10, 11, and 12

In this group of regions the freeze–thaw activity is predominantly in terms of freezes, but there are years when a month's temperature regime will be sufficiently low for activity during that month to be treated as a series of thaws. Region 7 is the small area around Boston, Massachusetts. Here it is obvious that the marine exposure considerably moderates the climatic regime and differentiates the Boston area from inland conditions. The climatic gradient is almost as pronounced in the southwest direction toward Connecticut and New Jersey. But northeastward, the coastal areas of Nova Scotia and Newfoundland experience conditions only slightly more severe than those in the Boston area.

Region 8 includes most of the Appalachian mountain and Cumberland plateau area. Here freeze–thaw activity occurs about eighty times yearly. Elkins, West Virginia, at 1,970 feet averages 85 freeze–thaw cycles per year and Pulaski, Virginia, at 2,180 feet experiences on the average 81 cycles per year. Fluctuations through the 34–28-degree F. zone are to be expected during the seven-month period of October through April. During the colder months minimum temperatures will drop to about 20°F. or slightly below. Freezes of two and three days duration are also experienced during the colder months. Very similar freeze–thaw regimes occur in Regions 9 and 10. Region 9 is part of the Great Plains area extending from the Rockies in Colorado eastward through Kansas. Average activity varies from 61 at Lawrence, Kansas, to 96 at Garden City, Kansas, in the central part of the region and to 113 at Colorado Springs, Colorado, in the foothills of the mountain chain. There are six months of activity in the eastern portion and seven months in the central and western portion of the region. Average minimum temperatures accompanying the freezes are in the mid-teens or slightly lower than in Region 8. Region 10 is in the lee of the Sierra Nevadas and freeze–thaw activity averages over a hundred cycles per year: Tonopah, Nevada, averages 103 cycles; Bishop, California, 114; and at Reno, Nevada, the average is 140. Freezes of more than one day are infrequent at Bishop and, therefore, the area is designated as subregion *a*. The other two stations are in subregion *b*. Minimum temperatures during the freezes average in the low twenties. Activity in the region extends over a seven- or eight-month period.

Of the remaining two regions in this group, Region 11 is quite small and is limited to the immediate area of Pendleton, Oregon. In marked contrast to its surroundings, temperature conditions at Pendleton are only low enough during one January in every four or five for the activity to be regarded as a series of thaws. On the average about forty-six freeze–thaw cycles occur each year. Minimum temperatures with the freezes are in the lower twenties and two- or three-day freezes occur in the colder months. Region 12 extends along the west coast littoral between Eureka, California, to just north of Prince Rupert, B.C. In about one January in five or six years cold arctic air spills over the mountain barriers to these coastal areas. With the consistently lower temperature during these periods the activity is regarded as a series of thaws. For such an extended north–south exposure the range of the freeze–thaw frequencies is small, 15 at Portland, Oregon, and 24 at Prince Rupert, B.C. Minimum temperatures are in the mid-twenties but drop slightly at the more northern stations.

In this group are the six regions of 7 through 12. Representative station diagrams presented in Figure 4 under Group III are the following: Region 7, Boston, Massachusetts; 8, Elkins, West Virginia; 9, Garden City, Kansas; 10, Tonopah, Nevada; 11, Pendleton, Oregon; and 12, Portland, Oregon.

Group IV: Regions 13, 14, 15, 16, and 17

The freeze–thaw characteristic of this group is the predominant series of thaws during the colder months. Yet, during some years, the temperature regime is warmer than normal and the cycles are then considered as a series of freezes. Region 13, comprising the coastal areas of Nova Scotia and Newfoundland, is on the east coast. Activity extends over a six-month period with freezes or thaws of three and four days duration from November through February. Total activity ranges from about 45 to 52 cycles. Conditions in Region 14 are somewhat similar. Region 14 extends from central Illinois eastward to include much of the lower half of the New England states. Freeze–thaw activity extends over a six- or seven-month period with average activity for the year of high fifties to the low seventies. Freezes or thaws of three and four days duration are not uncommon with an average temperature departure of 6 to 8 F. degrees from the levels of 28°F. and 34°F.

In the northern high plains area comprising Region 15, the freeze–thaw frequency ranges from 72 at Billings, Montana, to 111 at Ogallala, Nebraska. Activity is spread over a seven-month period. Temperature departures from 34°F. during the winter thaws average 8 to 12 F. degrees and there are occurrences of temperatures remaining above 28°F. for periods of two and three days. Region 16 is in the intermontane area of the western mountain complex. Again activity is high, ranging from 54 at Spokane, Washington, to 168 on the high plateau at Durango, Colorado. Freeze–thaw extends over a seven- to eight-month period but activity may extend over a nine-month period at Elko, Nevada. In most of the area the temperature departure curve shows a marked dip during either December or January, indicating relatively more severe temperatures at these times than in the high plains of Region 15.

Region 17 of this group encompasses the coastal zone of southern Alaska. Juneau experiences 52 cycles per year and Yakutat 72 per year. March and April account for much of the activity, which follows a pattern similar to that on the adjacent mountain ranges. The minimum temperatures during March are lowered markedly by repeated incursions of much colder air from the mountainous areas, especially in the vicinity of Yakutat. This colder air is rapidly modified by the maritime conditions which predominantly prevail at the stations. Therefore, even though March conditions at Yakutat satisfy the freeze–thaw characteristics for the next grouping of regions, the station has been retained in this particular grouping because of the rapid modification that takes place. Freezes or thaws of three and four days duration is frequent; and noticeable also is the colder temperatures during January.

Representative stations presented in Figure 5 under Group IV are the following: Region 13, Yarmouth, N.S.; 14, Akron, Ohio; 15, Ogallala, Nebraska; 16, Elko, Nevada; and 17, Juneau, Alaska.

Group V: Regions 18, 19, 20, 21, 22, and 23

The delimiting factor for this group of regions is that at least for one month the freeze–thaw cycle prevails only as a series of thaws. In Region 18, which extends from near the New York state border northeastward between the St. Lawrence River and the coastal zone, yearly activity ranges from 55 to 75 cycles over an eight- or nine-month period. Winter severity of this region is moderated by frequent thaws: for practically one-third of the days during the winter months, the maximum temperatures can be expected to reach the 38 to 42°F. level with thaws of two and three days duration being experienced each month. Conditions in Region 19 extending across eastern Iowa, northern Illinois and southern Wisconsin, central Michigan, and into Canada are less severe than in Region 18. Total activity averages less as well as the number of months of activity. A contributing factor is the earlier transition in the spring in Region 19 as compared to Region 18.

Region 20 extends from central Iowa northwestward to the Canadian Rockies from Lethbridge, Alberta, to Ft. St. John, B.C. Activity extends over an eight- to nine-month period, with January and, in some cases, also February showing a marked reduction in activity compared with the other months. Lethbridge with 85 cycles per year is almost an anomalous situation and presents a freeze–thaw pattern quite similar to stations in the immediate mountain complex. It would be possible to separate the region practically in half on the basis of the activity during November. The southwestern half has a less severe winter than the northeastern strip. Activity in the southern Canadian mountain complex of Region 21 is very similar to the activity pattern in Region 20. Region 21 also extends into the United States as two prongs. The western prong extends along the Cascades and the Sierra Nevadas and is designated sub-region *b* because of its milder winter regime in comparison with the other areas of the region. The eastern prong extends into the United States as the northern Rocky Mountains. Activity in this mountainous region is quite high, usually averaging over 100 cycles per year and spread over a nine- to ten-month period. Thaws of two and three days duration during the winter period are not uncommon in the mountain valleys.

Regions 22 and 23 in south-central Canada and north-central United States experience winters with temperatures occasionally rising above the 34°F. mark but then only by a few degrees. Predominantly, the yearly total of freeze–thaw cycle is in the forties but there are two stations in Region 22 which definitely reflect the influence of the cold waters of Lake Superior. Just to the north is Franz, Ontario, which experiences 76 cycles over an eleven-month period, the longest period of continuous activity recorded in the study; to the south is Iron Mountain, Michigan, with 62 cycles per year. Both stations are in sufficient proximity to the lake to be influenced by air with a fetch from off the lake, yet fai enough inland so as not to be dominated by the lakes as is the case of Sault St. Marie. Another apparent anomaly is the placement of the northern boundary of this region in the vicinity of Moosonee, Ontario, at the southern tip of St. James Bay. This boundary is based principally on the April regime at the station. The regime shows the moderating influence of warm air which is brought in by the rather extensive lows moving along the St. Lawrence Valley. April freeze–thaw patterns at Nitchequon and Mistassine Post in Quebec also reflect this condition. Region 23 is a triangular area with its apex pointed southward, seemingly indicating the thrust of cold arctic air into the central regions of the United States. The continentality of Region 23 is indicated by the rapid transition occurring in the autumn and in the spring. In all, the pattern is more like that of the northern regions than those of the two regions to the east and west.

Representative station diagrams presented in Figure 5 for regions within this grouping are: Region 18, Millinocket, Maine; 19, Grand Rapids, Michigan; 20, Fort Peck, Montana; 21, Cranbrook, B.C.; 22, Val d'Or, Quebec; and 23, Winnipeg, Manitoba.

Group VI: Regions 24, 25, 26, and 27

Characteristic of this group of regions is daily temperature consistently below 34°F. for a stretch of at least one month. There now occurs a midwinter break in the freeze–thaw diagram. Region 24 consists of the interior valleys of the northern section of the Canadian mountain complex, whereas the surrounding mountains comprise Region 25. During two of the winter months in Region 24 the temperature occasionally rises above 34°F., but not in Region 25. Regions 26 and 27 occupying the central and northern sections of Canada are divided on similar basis. In Region 26 the cold–dry season lasts from one to four months, whereas in Region 27 the temperature may not rise above 34°F. for periods of four to eight months. The latter two regions have sub-regions along the eastern coasts indicating the greater activity and moderating influence caused by the proximity to the more open arctic waters.

Representative stations given in Figure 5 for the four regions of Group VI are: Region 24, Mayo Landing, Y. T.; 25, Dawson, Y.T.; 26, Trout Lake, Ontario; and 27, Baker Lake, N.W.T.

CONCLUSION

This study has developed a regional pattern in the freeze–thaw activity for an area comprising most of North America. Regionalization is based on a monthly analysis of the frequency, duration, and severity of periods of freezing and thawing weather. A certain grouping of the regions became evident during the study: the grouping reflects the increased severity in climate from south to north and from coastal areas inland. In general, it is the case of cold weather boundaries (occurrences of freezes) in the south and warm weather boundaries (occurrences of thaws) in the north. However, for the present, these group boundaries are in no sense more valid or important than those boundaries based upon criteria used in determining the regional divisions within the groups.

The freeze–thaw characteristic of the first three groups is predominantly in terms of freezes. In Group I, under consistently mild temperatures of its climatic regime, freezes do not occur with any regularity during any one particular month over a period of years. In Group II, however, under a more severe temperature regime, freezes do occur with some regularity at least for one month of the year. Activity in Group III is predominantly in terms of freezes, but occasionally the temperature regime during a winter month is sufficiently low for the freeze–thaw activity to be regarded as a series of thaws. For the other three groups of regions the characteristic activity during the colder month or months is predominantly in terms of thaws. In Group IV the freeze–thaw activity during the coldest month is most frequently in terms of thaws although the temperature regime is such that milder conditions can occasionally be expected and the activity then regarded as a series of freezes. But under the colder regime of Group V, the activity during at least one month is only in terms of thaws. The last group, Group VI, is comprised of those regions where for at least one month of the year the temperature remains consistently below the 34°F. mark.

The degree to which distribution of freeze–thaw activity reflects distributional patterns of precipitation, vegetation, and soils varies

considerably.[15] On comparing the distributional patterns of freeze–thaw and precipitation, several boundaries show a general level of agreement, whereas between freeze–thaw and vegetation and soils, the level of coincidence is quite low. However, a comparison of the freeze–thaw pattern with the geographical limits of individual crops and trees revealed several marked coincidences.[16] Whether these coincidences are real or merely fortuitous would be difficult to prove at present.

In conclusion, it is believed that this study presents two particular factors of interest. First, it presents a regional analysis of a significant temperature threshold. Whether this regionalization is a more accurate delineation of the respective climatic conditions prevailing in the various regions than that presented by the usual temperature statistics does require testing. Second, the study found a diagrammatic form of presenting freeze–thaw data most useful for making the regional analysis. Whether this or similar diagrams are more appropriate for presenting certain types of climatic information than methods usually used warrants consideration and further study.

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[15] To obtain a usable distribution pattern of precipitation, rainfall data for the same 172 stations were processed into diagrammatic form based on the average amount and number of days of precipitation for each month of the year. For vegetation and soils acceptable distributions were already available.

[16] For crops, distributions as shown by O. E. Baker, *A Graphic Summary of American Agriculture Based Largely on the Census* (Washington, D.C.: U.S. Department of Agriculture Miscellaneous Publication No. 105, May, 1931); for trees, those distributions presented by E. L. Little, Jr., "Important Forest Trees of the United States," *Yearbook of Agriculture* (Washington, D.C.: U.S. Government Printing Office, 1949), pp. 763–814.