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Late- and Postglacial Climatic Change in the Northern Midwest, USA: Quantitative Estimates Derived from Fossil Pollen Spectra by Multivariate Statistical Analysis

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Canonical correlation analysis provides a means of reconstructing quantitative time series of past climatic variables during the last 15,000 years from fossil pollen spectra collected at three sites in the northern Midwest. This multivariate statistical technique was applied to a spatial array of modern pollen and climatic data in order to derive a set of mathematical transfer functions. These transform the fossil pollen spectra directly into quantitative estimates of past climatic values. The basic sequence of climatic events that is reconstructed is in general agreement with previous studies of postglacial climates in the Midwest, but quantitative estimates for certain of the variables, e.g., temperature and precipitation, are given for the first time.

Fossil pollen from three cores collected from lakes in Wisconsin and Minnesota allow a preliminary reconstruction of past east-west and north-south gradients of the climatic variables. Because changes in the circulation patterns in midlatitudes are the principal mechanism causing fluctuations in temperature and precipitation, past records of the atmospheric circulation are reconstructed along with records of temperature and rainfall. The time series derived show that the most pronounced climatic change indicated in Wisconsin and Minnesota occurred at the end of the Pleistocene (the beginning of the Holocene). This change is particularly evident in the climatic variables related to temperature, which rose *ca.* 3.3°C. A decrease in snowfall also occurred.

During the Holocene, the most marked change appears in the results from Kirchner Marsh, where the amount of dry western air began to increase and the precipitation to decrease about 9500 B.P. A reversal of these changes occurred about 5000 B.P. In contrast, relatively little change occurred among the reconstructed values from Wisconsin; a marked east-west precipitation gradient, therefore, developed in this region of the Midwest from 9500 to 5000 B.P.

The development of a theoretical understanding of climatic change during the Holocene requires a firm factual basis consisting of quantitative time series of climatic variables and their regional patterns during this 10,000-year period. These records should reveal the magnitude and character of the changes that have occurred. Since direct instrumental measurements of the climatic variables are available for only a minute portion of this time, indirect sources of climatic data, such as pollen profiles, must be

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used. These sources need to be calibrated in terms of climatic variables. In order to accomplish this task, an objective statistical method similar to that used by Imbrie and Kipp (1971) or that used by Fritts *et al.* (1971) is appropriate.

Fossil pollen data have long been recognized as an excellent source of Pleistocene climatic information (see von Post, 1967—an English translation of his 1916 paper). Although individual grains can seldom be identified at the species level, the quantitative nature of pollen spectra, either in relative or absolute terms, allows inferences to be drawn about the state of past vegetation and climate. Most interpretations of quantitative pollen data provide only qualitative descriptions of the climate (Wright *et al.*, 1963; West, 1961), but some quantitative estimates are available (Nichols, 1967; Iversen, 1944; Rampton, 1971; Cole, 1969). Of this latter group of studies, only that by Cole (1969) has utilized multivariate statistical methods for reconstructing the climatic values. A search of the literature reveals no other attempts to formulate mathematical transfer functions that can translate records of fossil pollen directly into quantitative climatic estimates. This paper derives these functions by means of canonical correlation analyses of spatial arrays of modern pollen and climatic data, uses these functions on fossil pollen spectra, and examines the results.

In the specific application in this study, transfer functions derived from modern pollen data collected in central North America were used on fossil pollen spectra obtained from three lakes situated in the northern Midwest. The locations of these three sites of fossil pollen, Kirchner Marsh (KM), Disterhaft Farm Bog (DFB), and Lake Mary (LM), are shown in Fig. 1. Figure 2 presents a summary diagram of certain of the pollen types for each of the three sites. A brief consideration of this figure confronts one with the basic problem faced in this paper. Differences exist among the pollen records, but what do these differences mean in climatic terms?

THE METHOD

In order to answer this question, a method is required that can transform pollen data directly into quantitative estimates of certain climatic variables. This transformation may be visualized in the following form:

$$PB = C \qquad (1)$$

where P represents the pollen data in quantitative terms, C represents the climatic estimates, and B represents a set of transfer functions that act to transform the pollen data into climatic information. If one treats Eq. 1 as a qualitative model, it provides an adequate, though general, description of the interpretive process used by palynologists in extracting climatic information from their data.[3]

Given this representation of the problem, with the fossil pollen data known, the derivation of past climatic estimates is straightforward once the transfer functions are established. Palynologists, however, have not

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[3] This formulation may actually present an oversimplified view of the interpretive process in palynology. A more complete description is provided if the derivation of climatic information from pollen spectra is considered a two-step process (see Faegri and Iversen, 1964) represented by the following equations:

$$PA = V \qquad (1a)$$

$$VD = C \qquad (1b)$$

where A represents a set of transfer functions that transform pollen data into vegetation estimates, V represents estimates of the vegetation, and D represents a set of transfer functions that transform the vegetation estimates into climatic estimates. (For some palynologists Eq. 1a provides a complete description of palynological interpretation, since they consider the reconstruction of the past vegetation as an end in itself). These two equations reduce to the form of Eq. 1 if Eq. 1a is substituted into Eq. 1b, i.e.,

$$P(AD) = C \qquad (1c)$$

If $AD = B$, then Eq. 1c is Eq. 1 exactly.

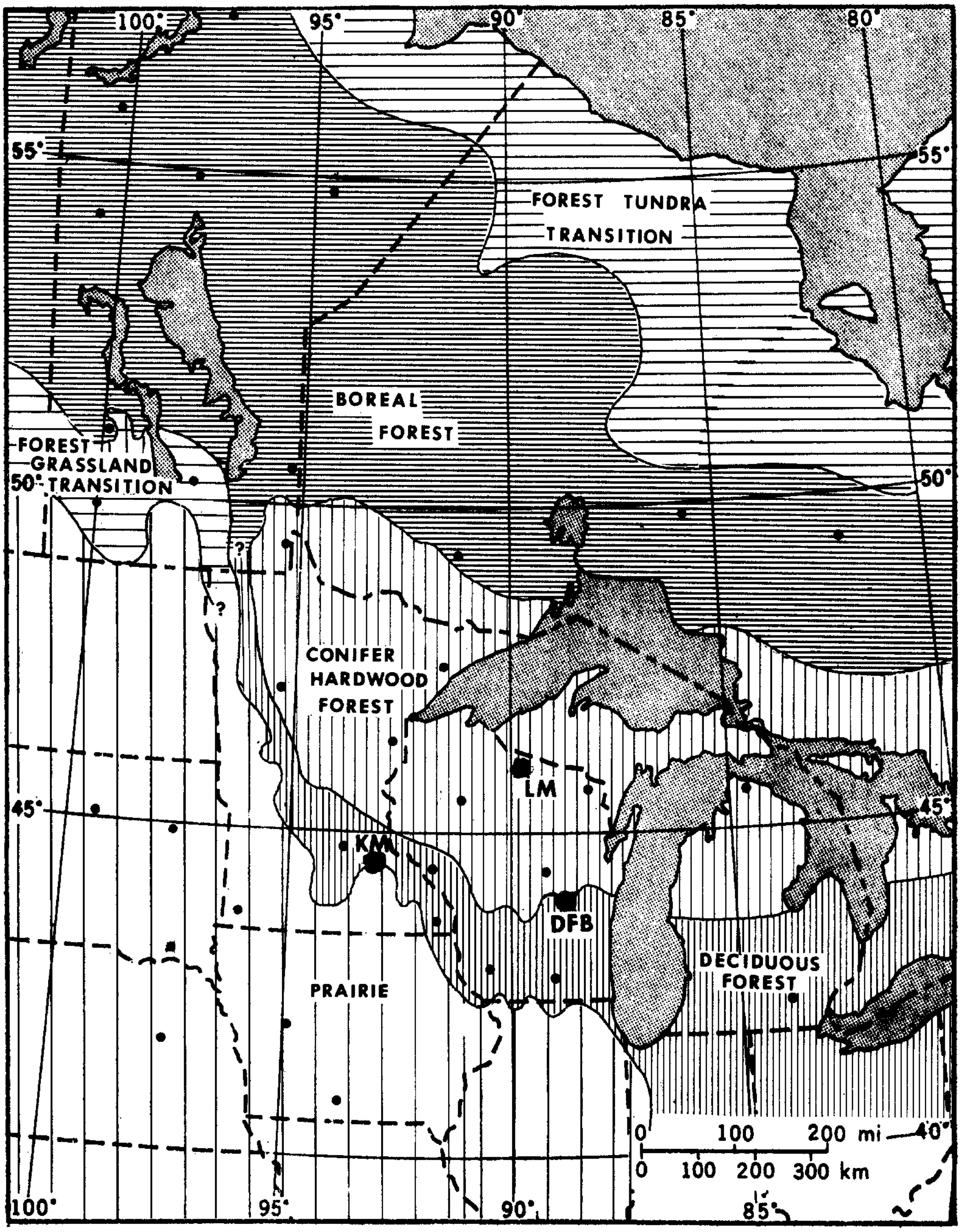

FIG. 1. Location of the three fossil pollen sites (large dots)—Lake Mary (LM), Disterhaft Farm Bog (DFB), and Kirchner Marsh (KM)—in their ecological setting. Vegetation map is adpated from Wright *et al.* (1963). Small dots indicate the locations of modern pollen samples that are labeled in Fig. 4.

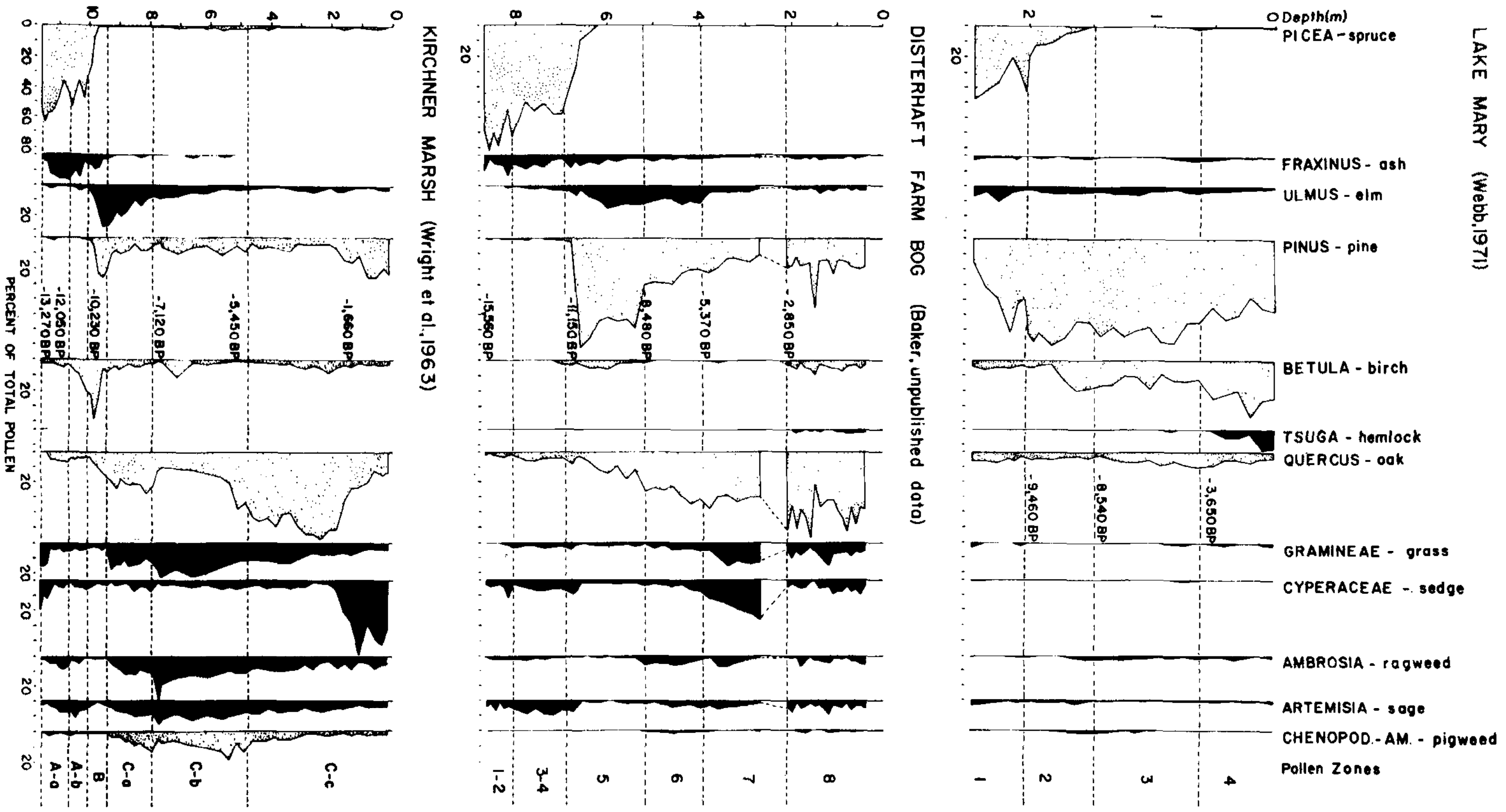

FIG. 2. Summary diagram of the fossil pollen at Lake Mary, Disterhaft Farm Bog, and Kirchner Marsh. The pollen zones at Lake Mary are those described by Webb (1971); at Disterhaft Farm Bog, by West (1961); and at Kirchner Marsh, by Wright *et al.* (1963). The pollen types with stippling are the ones included in the transfer functions derived in this paper.

standardly specified the transfer functions (B) in quantitative terms, but have arrived at their interpretations via a qualitative process which, though it may be represented by B, consists of a set of nonanalytically defined mental judgments based on each researcher's acquired experience and ecological understanding (Livingstone, 1969). The results of this type of interpretive process have generally produced only qualitative statements about the climate.

Recently in order to gain a stronger empirical basis for their climatic and vegetational interpretations, palynologists (Lichti-Federovitch and Ritchie, 1965, 1968; McAndrews, 1966; Davis, 1967) have collected samples of the contemporary pollen rain from surface sediments of lakes and bogs and examined the interrelationships of these samples with modern vegetation and climate. From these studies, based on the spatial intercorrelation of certain pollen types and climatic variables, these researchers have established mental associations, represented by B, that can be used to interpret records of fossil pollen. For certain vegetational studies, the relationships between spectra of modern pollen and data from the modern vegetation have been quantitatively specified (Davis and Goodlett, 1960; Livingstone, 1968; Andersen, 1969), and in one study (Ogden, 1968) correlation analysis of rank order was used to relate spectra of fossil pollen to spectra of modern pollen. The relationship to climate, however, has remained qualititative. In effect, these palynologists have qualitatively solved the following equation for B:

$$P_mB = C_m, \tag{2}$$

where m as a subscript denotes that modern pollen and climatic data are being used. Then assuming the climatic response represented by each pollen type has remained constant during the time interval discussed, these workers have used the same B (or rather those mental associations which comprise B) in order to interpret the fossil data. This step is schematically represented by the following equation:

$$P_fB = C_f, \tag{3}$$

where f as a subscript denotes that pollen of fossil origin is being used and past climatic data derived.

The logical next step given this procedure of interpretation is to take full advantage of the quantitative nature of the pollen and climatic data and solve Eq. 2 mathematically for B by using multivariate statistical procedures. This approach is the one used in this paper and produces a quantitative specification of B. The use of B in Eq. 3 then yields quantitative estimates of past climates.

In addition to the quantitative results, an important advantage gained by using this interpretive procedure is that the same results can be derived by all investigators. Given the same data analyzed in the same manner, the final results are fixed and obtainable by all. Modifications of these results are possible if different modern data are chosen or different schemes of analysis used. These modifications can also be derived by all workers. Future researchers will be better able to reproduce a previous interpretation and show exactly how any modification they make is derived. By examination of the derivation of the transfer functions B, these workers can gain knowledge about the ecological understanding used by the previous interpreter.

The chief disadvantage in using this methodology is that a more restrictive set of assumptions are needed than those involved implicitly in the use of previous interpretive schemes. The results derived in this paper depend, first, upon climate being the ultimate cause of the changes in the pollen records (Bryson and Wendland, 1967), second, upon a constancy in the climatic response of the pollen types used, and third, upon the ability of linear relationships to approximate adequately the relationship between each climatic variable and a set of pollen types. For the scale, both in time and in space, considered in this study, the above assumptions are probably valid enough, such that the results derived in this study provide a good first approximation of the climatic changes that occurred. Future work will certainly be necessary in order to refine this methodology and improve the reliability of the results.

The use of multivariate statistical techniques in this paper creates a quantitative empirical model based on the computational procedures used in statistical models. This type of model building is well-recognized in observational science (see, Perala, 1971), especially in "studies where dependency relations among measured values are obscured in part by complex interrelationships" (Krumbein and Graybill, 1965, p. 19), and contrasts sharply with more exact process-oriented modeling efforts, e.g., the numerical models of the atmosphere. These latter efforts produce models that are deduced primarily from theory because most of the physical laws governing the phenomena are known. These types of models, however, cannot be used yet in palynological work because they require knowledge not currently available, i.e., knowledge about the physics of pollen dispersal and about the exact role of climate in determining the distribution of vegetation.

The specific method of analysis employed in this study is canonical correlation analysis (Hotelling, 1936). It is used in order to distill from the data the relationships between the pollen and climatic variables. This technique finds an ordered set of mutually orthogonal patterns among the climatic data and an ordered set of mutually orthogonal patterns among the pollen data. The mutually orthogonal patterns are called canonical variates. The correlations between respective pairs of variates (each pair is composed of one variate from each set) are the canonical correlations. The ordering of the variates in each set is such that the first pair of variates is maximally correlated; the second pair is next most correlated; and, in general, the successive pairs show maximum correlation if the previous pairs are excluded.

As in principal component analysis (Morrison, 1967), the first few variates selected (like the first few components) reflect the information in the data, and the higher-order patterns are more a product of the noise in the data. Those pairs of variates that are significantly correlated (Glahn, 1968) are used to calculate a set of canonical regression-coefficients that serve as the transfer functions. These transform the pollen data directly into estimates of the climatic variables. A more thorough discussion of this technique in mathematical terms is given in the Appendix.

THE DATA

Since the transfer functions are derived from observations rather than deduced from theory, the relationships between pollen and climate that are incorporated in the transfer functions are confined to those relationships included in the modern data. Therefore, if the transfer functions are to transform the fossil pollen data accurately into climatic values, the modern data need to be selected with some care.

Geographical Distribution of the Modern Data

The modern pollen and climatic data are from the region shown in Fig. 3 and are located around the three fossil sites. (The sources of the pollen spectra at each site are given in Table 1.) The irregular spacing of the observation points results from the limited number of collections of modern pollen available. With a denser set of points, a regular grid might be used to space the samples. Where several sites are close together, the pollen spectra are averaged in order to give the representative pollen spec-

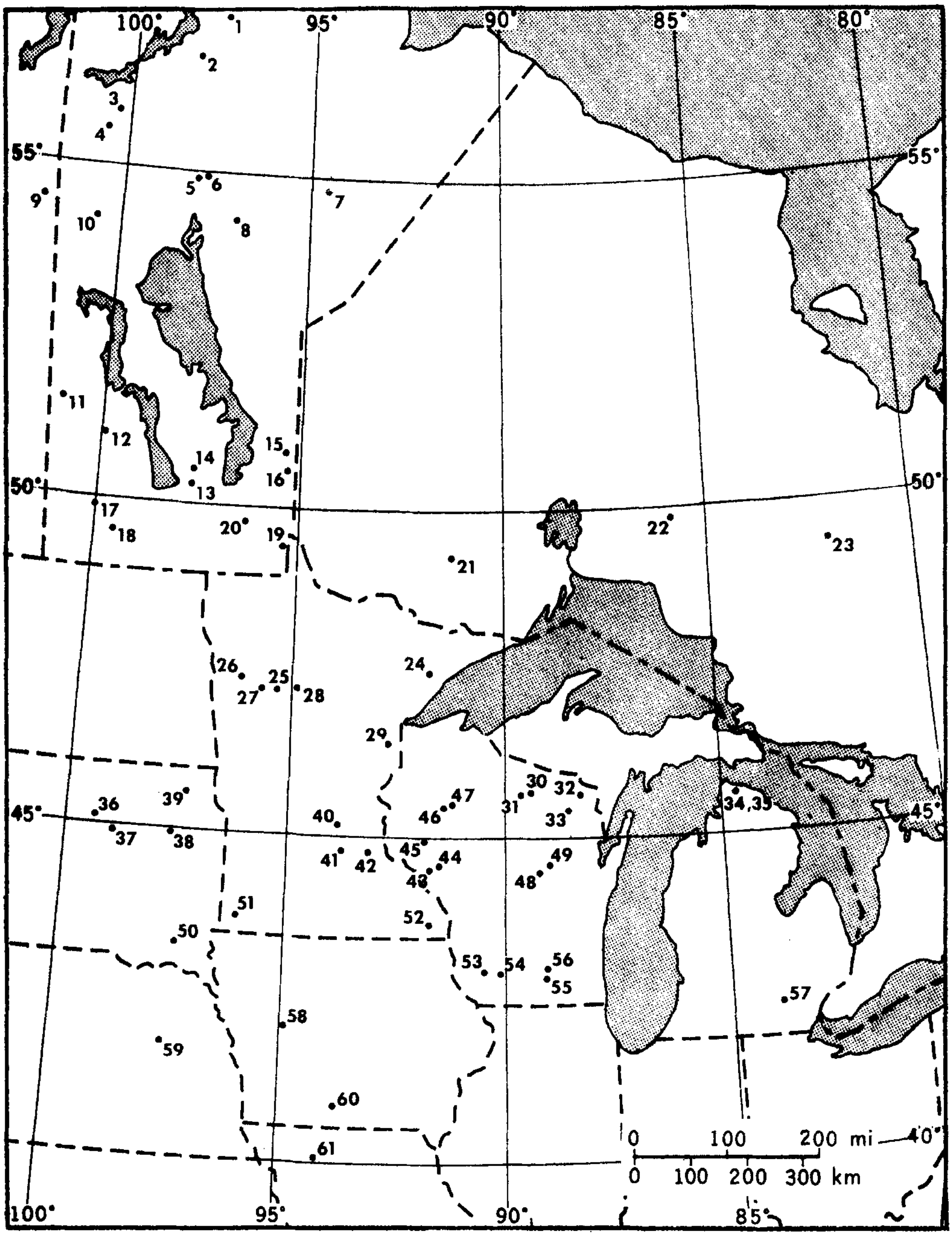

FIG. 3. Location of the modern pollen samples used in this study. Table 1 gives the references in which the data from each site are reported.

trum from the region and to maintain an even spatial distribution of the samples.

Among the criteria considered in selecting the areal distribution of the set of samples, the most important requires that the standard deviation and range of a pollen type in the modern record be greater than or equal to the standard deviation and range of that type in a core. For certain pollen types, inclusion of contiguous modern sites near the fossil sites allowed this requirement to be met. For other pollen types, values comparable to the fossil values were not to be found in additional sites. This problem is discussed in the next section.

From the geographical array of samples shown in Fig. 3, two sets of samples were chosen. The first set, designated as REG-34, is the most even and most nearly complete network of stations that could be assembled for this area of North America (see Fig. 4). (REG-34 is an abbreviation for regional

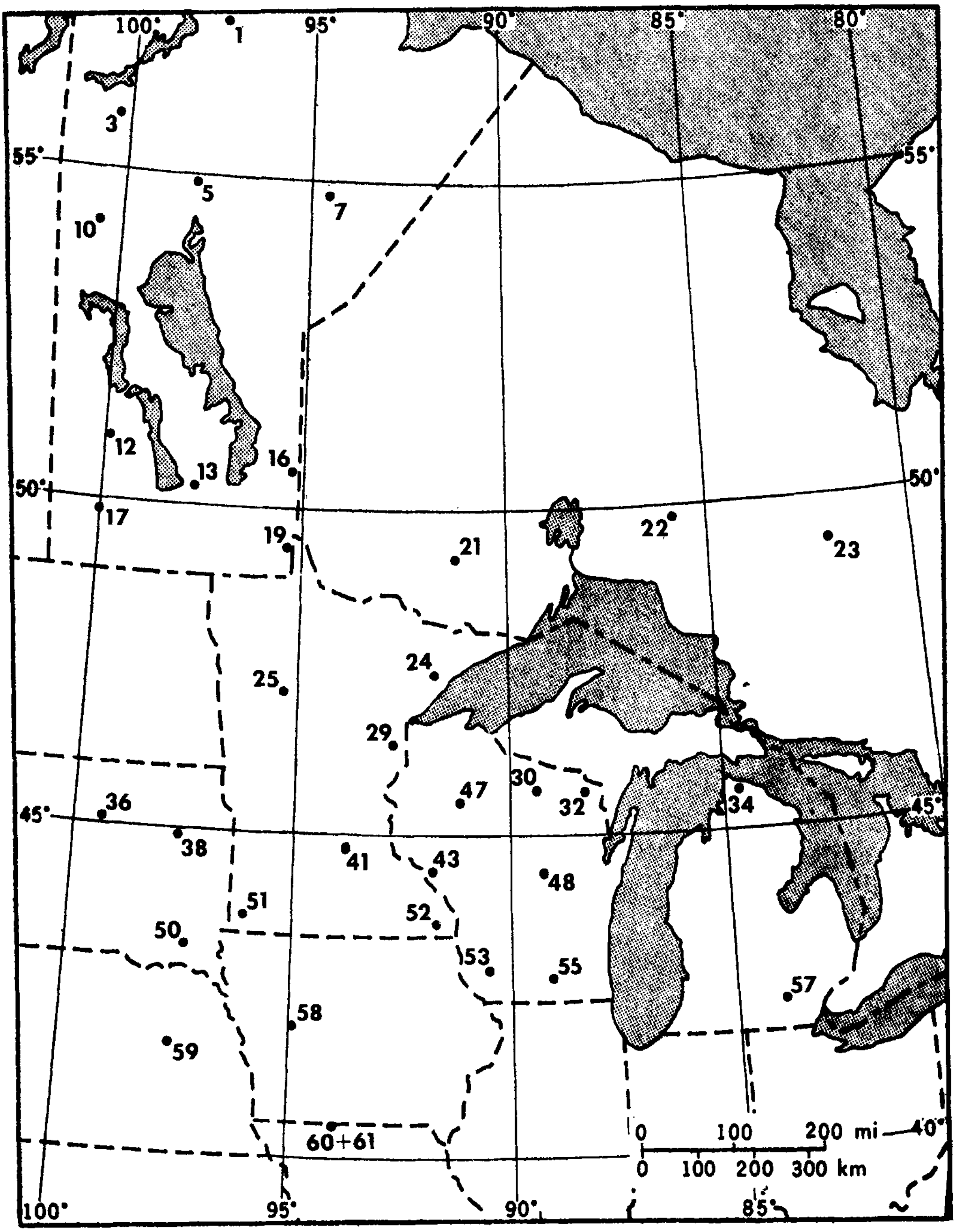

FIG. 4. Location of the samples included in REG-34.

TABLE 1

SOURCES OF SAMPLES OF MODERN POLLEN[a]

Sample	Reference	Material
1 Sample number 111	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
2 Sample numbers 113 and 114	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
3 Sample numbers 115 and 127	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
4 Sample numbers 122 and 128	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
5 Sample numbers 118, 121, 123	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
6 Sample numbers 39, 116, 117	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
7 Sample numbers 119 and 120	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
8 Sample numbers 124, 125, 126	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
9 Sample numbers 56–61	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
10 Egg Lake	Cole, 1969	fresh *Sphagnum*
11 Sample numbers 85–88	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
12 Sample numbers 89–93	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
13 Sample number 104	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
14 Sample number 80	Lichti-Federovitch and Ritchie, 1965	surface sediment—lake
15 Sample numbers 62–65	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
16 Sample numbers 66–69	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
17 Sample number 101	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
18 Sample numbers 85–88	Lichti-Federovitch and Ritchie, 1965	surface sediment—lake
19 Sample numbers 75 and 84	Lichti-Federovitch and Ritchie, 1965	surface sediment—lake
20 Sample number 76	Lichti-Federovitch and Ritchie, 1965	surface sediment—lake
Sample number 95	Lichti-Federovitch and Ritchie, 1968	surface sediment—lake
21 Raven Lake	Cole, 1969	fresh *Sphagnum*
22 Klotz Lake	Cole, 1969	fresh *Sphagnum*
23 Remi Lake	Cole, 1969	fresh *Sphagnum*
24 Weber Lake top C.2	Fries, 1962	surface sediment—lake
top P.1	Fries, 1962	surface-peat
25 Thompson Lake	McAndrews, 1966	surface sediment—lake
Horse Lake	McAndrews, 1966	surface sediment—lake
Reichow Lake	McAndrews, 1966	surface sediment—lake
Terhell Lake	McAndrews, 1966	surface sediment—lake
Bad Medicine	McAndrews, 1966	surface sediment—lake
Bog D	McAndrews, 1966	surface sediment—lake
Bog A	McAndrews, 1966	surface sediment—lake
Martin Pond	McAndrews, 1966	surface sediment—lake
Cindy Lake	McAndrews, 1966	surface sediment—lake
26 Faith Pond	McAndrews, 1966	surface sediment—lake
27 McCraney Pond	McAndrews, 1966	surface sediment—lake
28 Stevens Pond	Janssen, 1967	surface *Typha* mat
29 Jacobson Lake	Wright and Watts, 1969	surface sediment—lake
30 Little Saint Germaine Lake	Webb, 1971	surface sediment—lake
Lake Tomahawk sample number 1	Webb, 1971	surface sediment—lake
Trout Lake sample number 1	Webb, 1971	surface sediment—lake
31 Lake Tomahawk sample number 2	Webb, 1971	surface sediment—lake
Sparkling Lake sample number 2	Webb, 1971	surface sediment—lake
Helmet Lake	Webb, 1971	surface sediment—lake
Weber Lake	Webb, 1971	surface sediment—lake
32 Emily Lake	Webb, 1971	surface sediment—lake
Hilbert Lake	Webb, 1971	surface sediment—lake
33 West Bass Lake	Webb, 1971	surface sediment—lake
Pine Lake (Forest Co.)	Webb, 1971	surface sediment—lake
Fay Lake	Webb, 1971	surface sediment—lake
Ellwood Lake	Webb, 1971	surface sediment—lake

TABLE 1

Sources of Samples of Modern Pollen [a]—Continued

Sample	Reference	Material
34 Sample number 1	Benninghoff, 1960	moss polster
35 Sample number 5	Benninghoff, 1960	moss polster
36 Sample number 31	McAndrews and Wright, 1969	dry duff
37 Sample number 32	McAndrews and Wright, 1969	duff and sediment in cattle tank
38 Sample number 33	McAndrews and Wright, 1969	duff
39 Pickerel Lake	Watts and Bright, 1968	surface sediment—lake
40 Sample number 6 Clearwater	Janssen, 1966	surface *Typha* mat
Sample number 12 Clearwater	Janssen, 1966	surface sedge swamp
Sample number 9 Lake Sylvia	Janssen, 1966	surface *Typha* mat
41 Rutz Lake	Waddington, 1969	surface sediment—lake
42 Lake Carlson	Wright, Winter and Patton, 1963	surface sediment—lake
43 Dead Lake	Webb, 1971	surface sediment—lake
Lake Eau Galle	Webb, 1971	surface sediment—lake
Merrick State Park Lake	Webb, 1971	surface sediment—lake
44 Silver Birch Lake	Webb, 1971	surface sediment—lake
Haeusser Farm Pond	Webb, 1971	surface sediment—lake
Thompson Lake	Webb, 1971	surface sediment—lake
45 Lake Menomin	Webb, 1971	surface sediment—lake
Tainter Lake	Webb, 1971	surface sediment—lake
46 Island Lake	Webb, 1971	surface sediment—lake
Amacoy Lake	Webb, 1971	surface sediment—lake
47 Marsh Mueller	Webb, 1971	surface sediment—lake
Bass Lake	Webb, 1971	surface sediment—lake
Park Lake	Webb, 1971	surface sediment—lake
48 Stratton Lake	Webb, 1971	surface sediment—lake
North Lake	Webb, 1971	surface sediment—lake
White Lake	Webb, 1971	surface sediment—lake
49 Twin Lake	Webb, 1971	surface sediment—lake
School Section Lake	Webb, 1971	surface sediment—lake
Silver Lake	Webb, 1971	surface sediment—lake
50 Sample number 11	Kapp, 1965	surface sediment—cattle watering tank
51 Sample number 12	Kapp, 1965	surface sediment—cattle watering tank
52 Sample number 14	Kapp, 1965	surface sediment—cattle watering tank
53 Monfort Pond	Webb, 1971	surface sediment—lake
Farm Pond in Valley	Webb, 1971	surface sediment—lake
54 Cox Hollow Lake	Webb, 1971	surface sediment—lake
Raemisch Farm Pond	Webb, 1971	surface sediment—lake
55 Gibbs Lake	Webb, 1971	surface sediment—lake
Lake Ripley	Webb, 1971	surface sediment—lake
56 Rock Lake	Webb, 1971	surface sediment—lake
57 Frains Lake	Davis, *et al.*, 1971	surface sediment—lake
58 Blackhawk Lake	Webb, 1971	surface sediment—lake
59 Sample number 9	Kapp, 1965	surface sediment—cattle watering tank
60 Sample number 18	Kapp, 1965	surface sediment—cattle watering tank
61 Sample number 19	Kapp, 1965	surface sediment—cattle watering tank

TABLE 1

SOURCES OF SAMPLES OF MODERN POLLEN [a]—Continued

Sample	Reference	Material
62 Mueller Lake	Webb, 1971	surface sediment—lake
63 Vejo Lake	Webb, 1971	surface sediment—lake
64 Meyer Lake	Webb, 1971	surface sediment—lake
65 Kolpack Lake	Webb, 1971	surface sediment—lake
66 Norrie Lake	Webb, 1971	surface sediment—lake
67 Berry Lake	Webb, 1971	surface sediment—lake
68 White Clay Lake	Webb, 1971	surface sediment—lake
69 Kroening Lake	Webb, 1971	surface sediment—lake
70 Bog Pond	Webb, 1971	surface sediment—lake
71 Pine Lake	Webb, 1971	surface sediment—lake
72 Partridge Crop Lake	Webb, 1971	surface sediment—lake
73 Wayside Pond	Webb, 1971	surface sediment—lake

[a] Where two or more samples are listed after a number (e.g., number 2 or number 25), these samples were averaged together. This average spectrum was then used in the study.

pollen, 34 samples.) It is the array used to develop the pollen–climate relationships (i.e., transfer functions) to be applied to the fossil pollen data. REG-25 is an independent set that is contained within REG-34 geographically (see Fig. 5). This smaller array of samples is used to test the accuracy of the transfer functions derived from REG-34.

Pollen Variables

Eight pollen variables were used in the final analysis. They were pine (*Pinus*), spruce (*Picea*), birch (*Betula*), oak (*Quercus*), maple (*Acer*), hickory (*Carya*), walnut (*Juglans*), and pigweed (Chenopodiaceae). This set of pollen types, though much reduced from the set commonly included in palynological studies, is sufficient to reveal the major zones on each of the fossil diagrams and provides a sufficient sample for testing the methodology introduced in this paper.

Of the 40 pollen types identified in one or many of the modern samples given in Table 1 and standardly included in the pollen sum (Wright and Patten, 1962), 20 had to be eliminated because they either were not universally recorded, e.g., white pine and red and/or jack pine, or were never present in large enough quantities to be adequately sampled in a statistical sense. Using similar reasoning, Imbrie and Kipp (1971) removed all species of Foraminifera that never appeared in proportions greater than 2%. Composite family (Tubuliflorae and Liguliflorae), rose family (Rosaceae), legume family (Leguminosae), grape family (Vitaceae), and poplar (*Populus*) pollen were among the pollen types included in this group.

From the remaining 20 pollen types, five further were removed because their maximum values in fossil samples were two to five times greater than any modern values. These types were elm (*Ulmus*), hornbeam (*Ostrya-Carpinus*), tamarack (*Larix*), ash (*Fraxinus*), and hazel (*Corylus*). Application of transfer functions that include these pollen types to pollen spectra of fossil samples that contain the highest values of these types produces improbable results, e.g., minus 3 months of Arctic air during the Holocene (see the description of the climatic data for a definition of Arctic air). Imbrie and Kipp (1971) confronted a similar problem when they applied factor analysis techniques to data sets including certain species of Foraminifera.

With respect to these five pollen types, the present, as represented by the modern data used in this study, does not seem to provide an adequate key to the past. Since the highest values of these pollen types occur during the late-glacial and the early postglacial, these values may reflect certain conditions peculiar to a time when the landscape was just beginning to recover from the effects of glaciation, e.g., by reforestation and development of new drainage patterns. Were transfer functions developed only to be applied to the fossil pollen of the past 8000 years, these types could be included in this

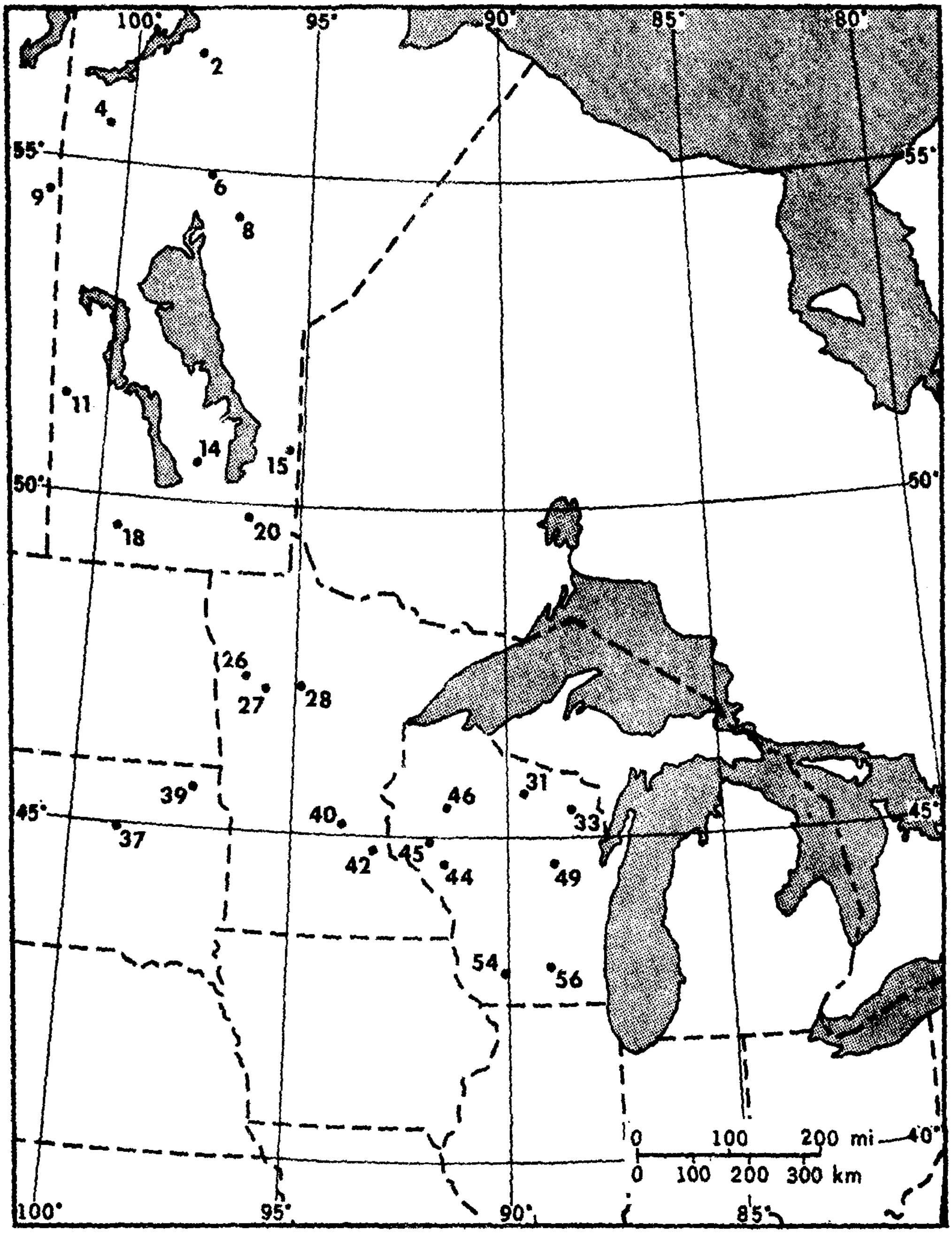

Fig. 5. Location of the samples included in REG-25.

study. Preliminary studies showed that inclusion of these pollen types produces essentially the same results as are presented in this study for the last 8000 years.

Ragweed (*Ambrosia*) pollen was excluded for just the opposite reason, its modern values are much larger than any of its fossil values. Its large numbers reflect the disturbed condition of the contemporary landscape and are probably not aligned with the climatic variables in the way the fossil values of ragweed were.

Since the transfer functions are basically a least-squares fit between each climatic variable and a linear combination of pollen variables, the statistical significance of the fit is increased with the increase in the ratio of observations to variables. In order to increase this ratio in this initial study, a final group of alder (*Alnus*), grass (Gramineae), basswood (*Tilia*), fir (*Abies*), willow (*Salix*), and sage (*Artemisia*) were left out. More recent studies (Webb, unpublished data) have shown that the inclusion of these pollen types does not change the major trends in the results, and these taxa may be included in future studies, especially when more modern pollen sites are included.

The values of the pollen types included in this study were percentages of a pollen sum including the eight pollen types plus fir, willow, and sage. The three additional pollen types were added because the derived sets of canonical variates were not mutually orthogonal when these variates were calculated using pollen percentages based on a pollen sum of just the eight pollen variables. This use of 11 pollen types in the pollen sum represents an empirical solution to this problem. Future work needs to be done in order to clarify the exact cause of this difficulty. Minor pollen-types were added because they do not appear in large enough numbers to affect the percentages of the eight pollen variables much, and three were needed because one or two were absent in some of the samples.

Climatic Data

The values of the climatic variables were derived at each of the modern pollen sites by interpolation from mapped climatic data. Three sets of climatic variables were used. One is five values representing the number of months duration per year of five air masses that affect the Midwest. The second is the frequencies during July or four of the same air masses plus a fifth, continental Tropical air. The third set contains seven of the standardly observed climatic measures that are likely to affect plant growth.

In the third set, the two primary variables of interest are the July mean temperature and the rainfall during the growing season. These particular measures were chosen since they represent aspects of the temperature and precipitation likely to have an effect on the plants, since these variables measure a part of the plant's environment during its active period of growth. The length of the growing season specifies the duration of this period, and degree days (above 42°F) measure its warmth. The number of hours of sunshine reflect the amount of radiation received at a station. Snowfall provides a measure of the other component of the annual precipitation. Also, snow can have an important insulating effect on plants during winter as well as provide an early spring supply of moisture (Oosting, 1956). Precipitation minus potential evaporation is included as a measure of the moisture stress; it is known to be an important parameter in the growth and distribution of plants (Sellers, 1965). The values of these variables were mainly obtained from "The Climatic Atlas of the United States" and "The Climates of Canada for Agriculture" (Chapman, 1966). Other sources used were "Climatological Atlas of Canada" (Thomas, 1953), "Climatology of Cold Regions" (Wilson, 1969) and "Monthly Records" of the Canadian Department of Transportation.

The frequency and duration of the air masses were derived by Bryson (1966; unpublished maps) in order to describe the distributions of air masses within North America. The frequencies are calculated by partial collective analysis (Bryson, 1966) of the multimodal arrays of the daily maximum temperature for July, and the duration values are derived from charts depicting the streamlines of monthly resultant winds over North America. The two sets of data may contain internal inconsistencies, because the resultant wind data were recorded during the 1930's and the maximum temperatures were measured between 1945 and 1955 (Bryson, 1966).

One feature of the maps of the air mass durations is the sharp gradients depicted. Changes of 4-months duration can occur within 100 miles. These regions of steeper gradients are used by Bryson to demarcate different climatic regions (see Fig. 33 in Bryson, 1966), and the positions of these gradients coincide with vegetation boundaries (see Fig. 7 in Bryson *et al.,* 1970).

Table 2 gives the frequencies of the air masses during July and their duration recorded in selected regions of Wisconsin and Minnesota. This table also lists the months when a given air mass prevails. The air mass duration values show that the four sets of air streams invading the northern Midwest—Arctic (A), maritime Tropical (mT), Return Polar (R), and Pacific-south (Ps)—dominate during different seasons of the year—spring, summer, fall, and winter, respectively (see Fig. 6–9). Each season has a particular pattern of air flow.

Examination of this table reveals that although the mean resultant streamlines are from the south in July, the most frequent air mass is Pacific-south. This seeming discrep-

TABLE 2

OBSERVED VALUES OF AIR MASS DURATIONS AND JULY AIR MASS FREQUENCIES IN MINNESOTA AND WISCONSIN (FROM BRYSON, 1966)

			Minnesota			Wisconsin	
Air mass durations		north	central	south	north	central	south
maritime Tropical (mT)	no. of months	3	3	5	3	3	3
	name of months	Ju Jy Ag	Ju Jy Ag	Ap My Ju Jy Ag	Ju Jy Ag	Ju Jy Ag	Ju Jy Ag
Return Polar (R)	no. of months	1	1	2	2	2	2
	name of months	O	O	S O	S O	S O	S O
Pacific-south (Ps)	no. of months	4	5	5	3	3	4
	name of months	S N D Ja	S N D Ja F	N D Ja F M	N D Ja	N D Ja	N D Ja F
Pacific-north (Pn)	no. of months	0	0	0	0	0	0
	name of months						
Arctic (A)	no. of months	4	3	0	4	4	3
	name of months	F M Ap My	M Ap My		F M Ap My	F M Ap My	M Ap My
July air mass frequencies (in %)							
maritime Tropical (mT)		7	12	18	7	12	20
continental Tropical (cT)				4		2	3
Pacific-south (Ps)		64	67	65	58	58	62
Pacific-north (Pn)		20	13	8	21	17	10
Arctic (A)		9	8	5	14	11	7

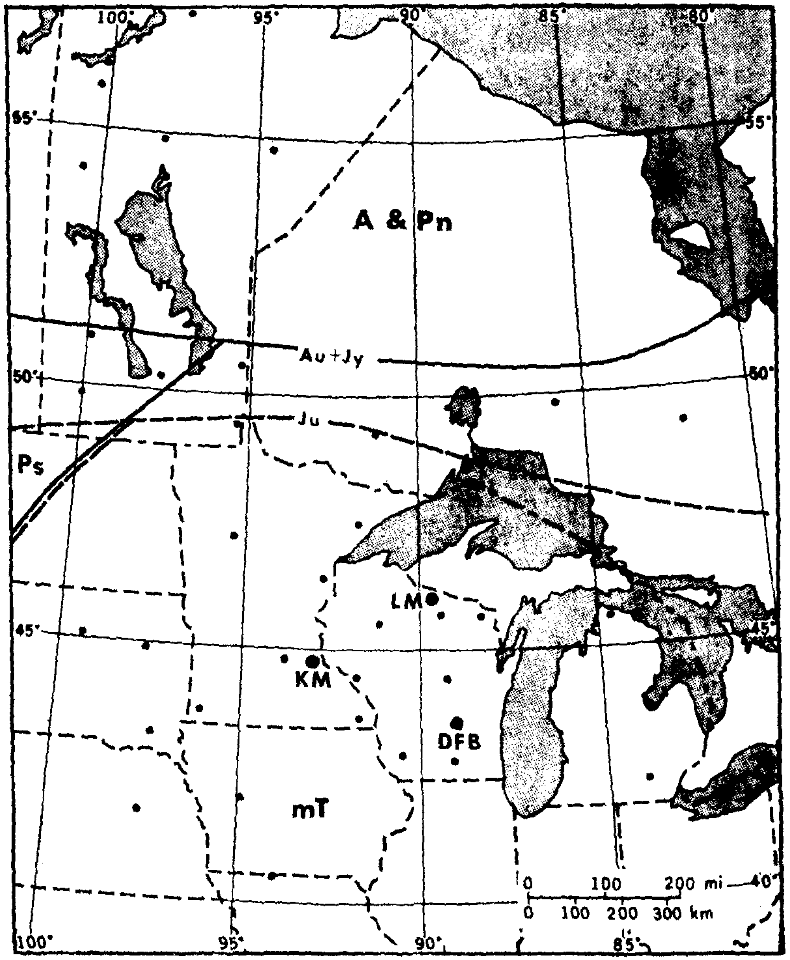

FIG 6 (left). Position of the air mass boundaries on the charts of the streamlines of the mean resultant winds (Bryson, 1966) for the winter months: November (N), December (D), January (J), and February (F).

FIG 7 (right). Same as in Fig 6 for the summer months: June (Ju), July

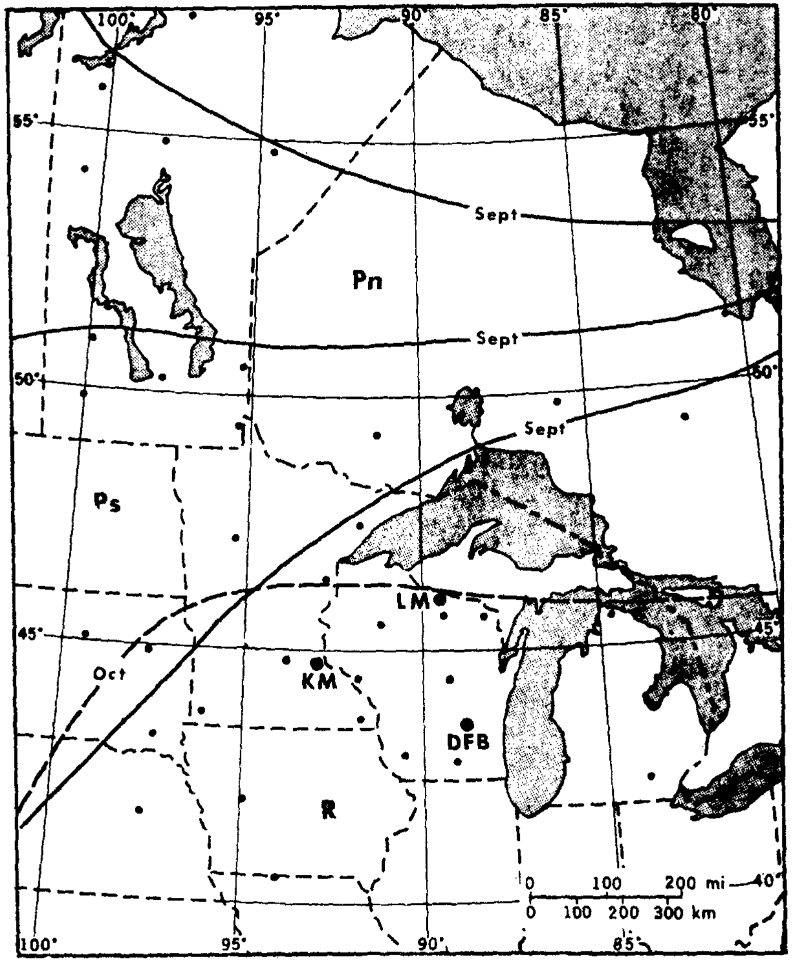

FIG. 8 (left). Same as in Fig. 6 for the spring months: March (M), April (Ap), and May (My).

FIG. 9 (right). Same as in Fig. 6 for the fall months: September (Sept) and October (Oct).

ancy cannot be explained in terms of the difference in the times when these data were collected. The resultant winds are from the 1930's and should if anything reflect the stronger zonal flow of that period. This situation implies that the winds from the south were stronger than those from the west during July.

In addition to the previously described sets of climatic variables, the latitude of each site was included as an independent measure of the climate. The day length is directly related to the latitude, and it is one factor of the climate at each fossil site that has changed negligibly during the last 15,000 years. Because the latitude is known at the three fossil pollen sites, it is included with the pollen variables in the independent set of variables.[4]

CALCULATION OF THE TRANSFER FUNCTIONS

Standardization of the Data

Before the modern data were subjected to canonical correlation analysis, they were standardized. The individual observations of each variable were transformed into standard deviation units by Eq. (A. 1) in the Appendix. The reason for rescaling all the variables is to remove the bias given certain variables with large absolute values in the units in which they are measured. The information contained in these variables can be overemphasized by their large absolute values and overshadow the information contained in other variables. This problem arises, in particular, because of the different scales used to measure the climatic variables.

By use of standardized data, the structure of the canonical variates is based on the correlation of the variables. A disadvantage of this operation is that it inflates the effect of the binomial errors (Faegri and Iversen, 1964) of the less frequently observed pollen variables, but preliminary studies show that the information in these variables would have little effect were these variables not rescaled.

Selection of the Transfer Functions

With the data standardized, the calculation of the transfer functions involved first applying canonical correlation analysis separately to a combination of the pollen data and each of the sets of climatic data. This step produced five pairs of canonical variates for each of the sets of air mass variables and seven pairs of canonical variates for the set of standard climatic variables. For the calculation of the transfer functions, only those pairs with significant canonical correlations are used (Glahn, 1968). Since no statistical test for significance exists, empirical methods were devised that helped establish which pairs of variates are insignificant. These are the pairs that either reveal little interaction between the pollen and climatic variables or do not represent general patterns in the spatial population of values. The first method is designed to show the size of the climatic variance accounted for by a given canonical variate. If it contributes little information about the climatic variables, the variate is excluded.

The second procedure involves determining which canonical variates represent general patterns in the sampled population of pollen and climatic values; these variates are retained. Those variates with patterns that only appear in one statistical sample are eliminated. These two types of variates are distinguished by use of a method similar to the one Imbrie and Van Andel (1964) applied when checking the significance of factors established by factor analysis of heavy mineral data. From an initial collection of data, Imbrie and Van Andel selected two independent sets of samples and applied a form of factor analysis to each set. They then compared the factors derived from the

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[4] A more complete description of the site by factors such as altitude, exposure, and parent material (for soil development) might be used in future studies. These factors, like latitude, influence the environment at the site and may be considered constant over certain periods of time.

two sets and used the similarity of respective factors from each set to infer that those factors were representative of the statistical population.

In order to use this same procedure in the present problem, two independent sets of surface samples, REG-30 (Fig. 10) and REG-28 (Fig. 11), were chosen by re-sorting REG-34 and REG-25. Both sets of samples cover the same area geographically and have a similar range of pollen and climatic values. REG-30 and REG-28, there-

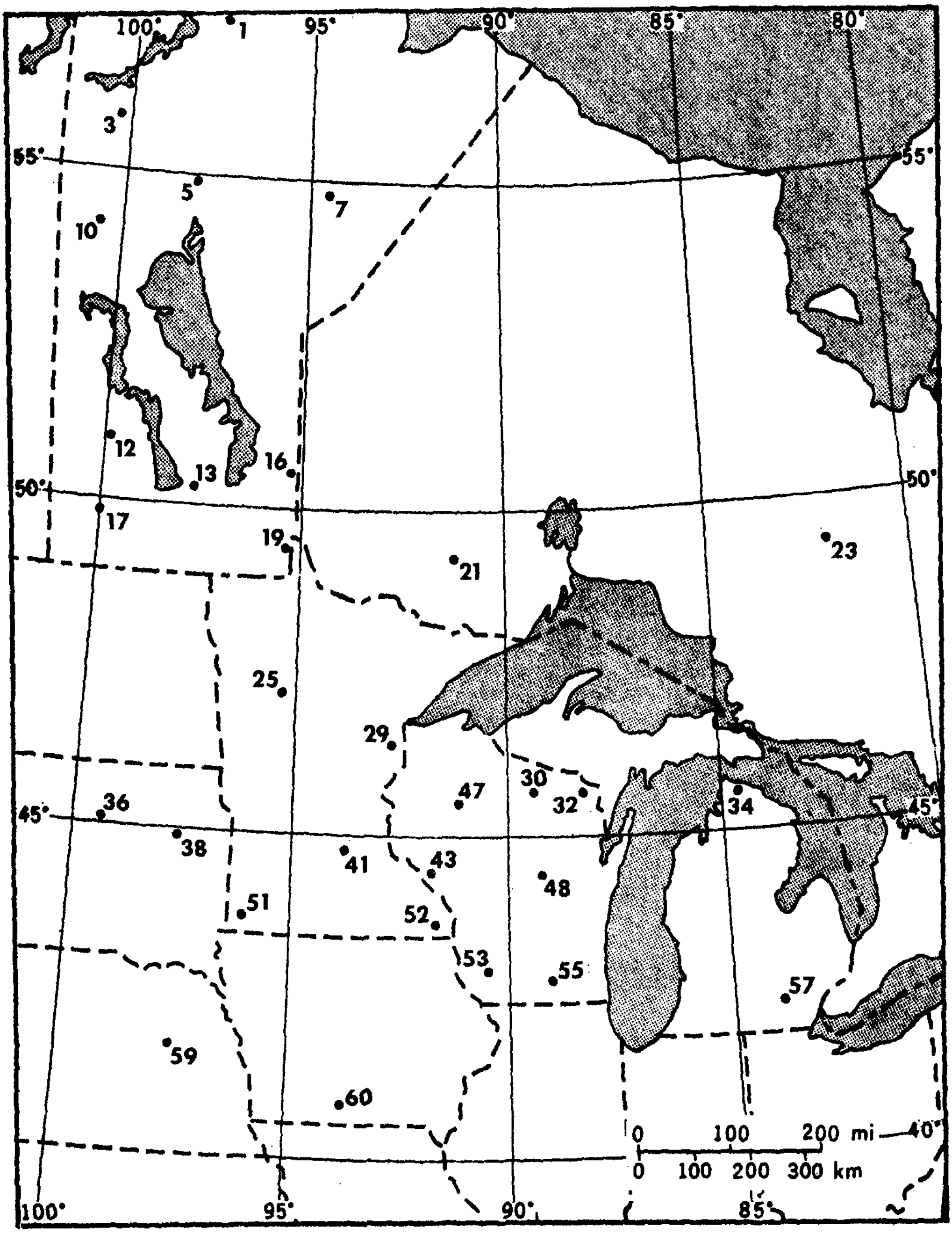


Fig. 10. Location of the samples included in REG-30.

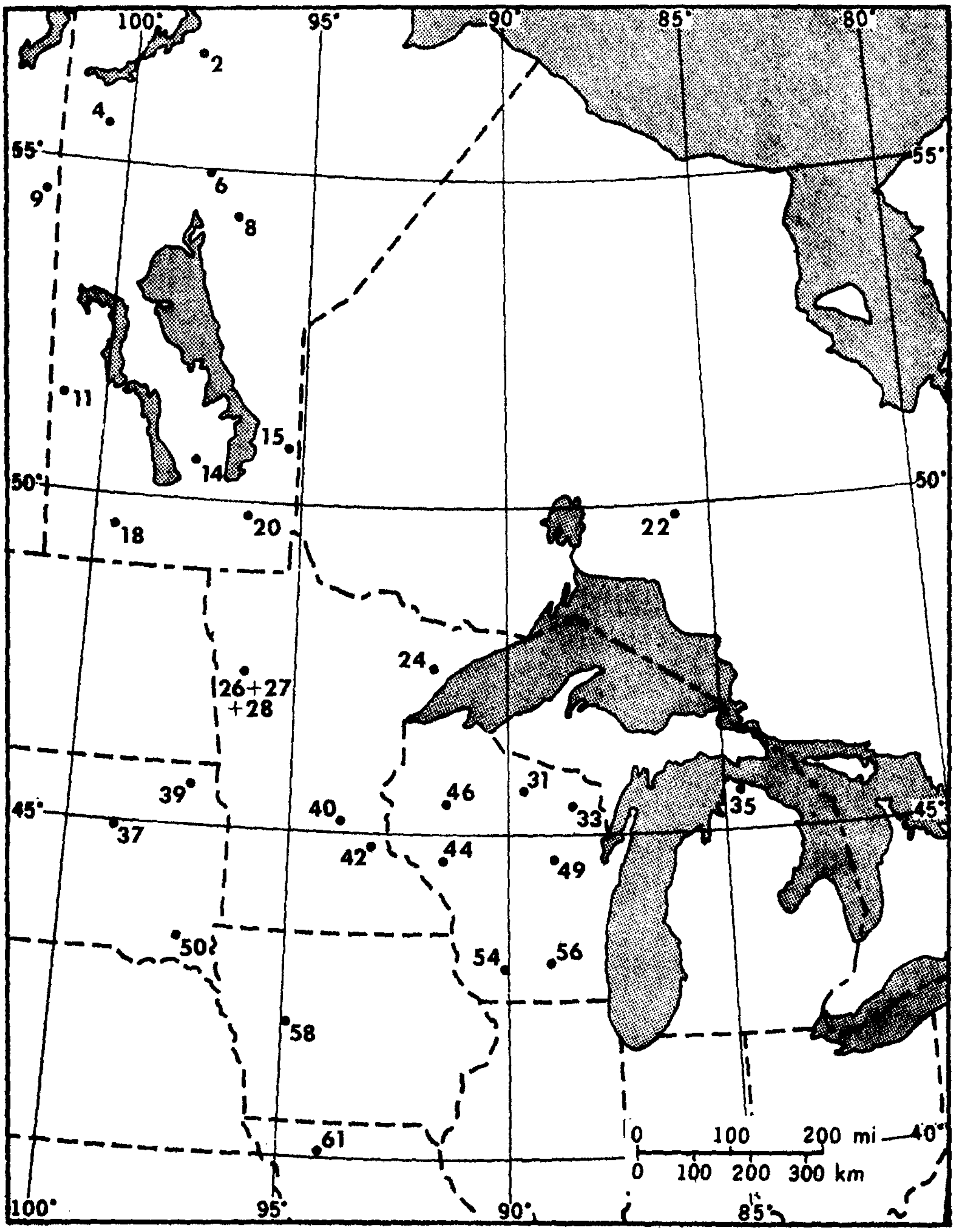


FIG. 11. Location of the samples included in REG-28.

fore, represent different samples from the same population. When both sets of data are analyzed by the canonical correlation technique, the canonical variates that reflect the general patterns of the population should appear in each analysis. The patterns unique to the given statistical sample will be restricted to one or the other sets of variates, except for chance similarities.

When these two different methods for determining the significant pairs of canonical variates were applied, their results agreed.

They indicate that only two canonical functions are needed for each of the sets of air mass variables and that three are needed for the standard climatic variables. Table 3 shows the data used in the first procedure. In the case of the air mass variables, the third canonical variate adds little to the explained variance, whereas the third canonical variate for the standard climatic variables still contains information, and it is the fourth and higher-order canonical variates that do not.

The comparison of the analyzed fields of the variates from REG-30 and REG-28 leads one to the same conclusion concerning the number of canonical variates to use. Maps of all three sets were constructed and examined, but only the air mass duration maps, which are exemplary, are presented in this paper (Figs. 12–17). These maps show similar patterns for the first and second canonical variates (Figs. 12 and 13, and Figs. 14 and 15), but the patterns of the third canonical variates in Figs. 16 and 17 are quite different. Only the first two variates were therefore used to calculate the transfer functions for the air mass duration variables.

The canonical regression-coefficients derived from REG-34 by the use of the speci-

TABLE 3

PERCENT VARIANCE EXPLAINED BY SUCCESSIVE CANONICAL VARIATES [a]

Standard climatic variables

Canonical variates	P–PE	Pg.s.	D.D.	Sun	Snow	G.S.	T
First	1	59	86	76	34	73	78
Second	68	24	3	17	33	3	11
Third	15		4		2	5	7
Fourth			1	1	15	8	
Fifth							
Sixth							
Seventh							
Total	88	87	95	95	87	89	96

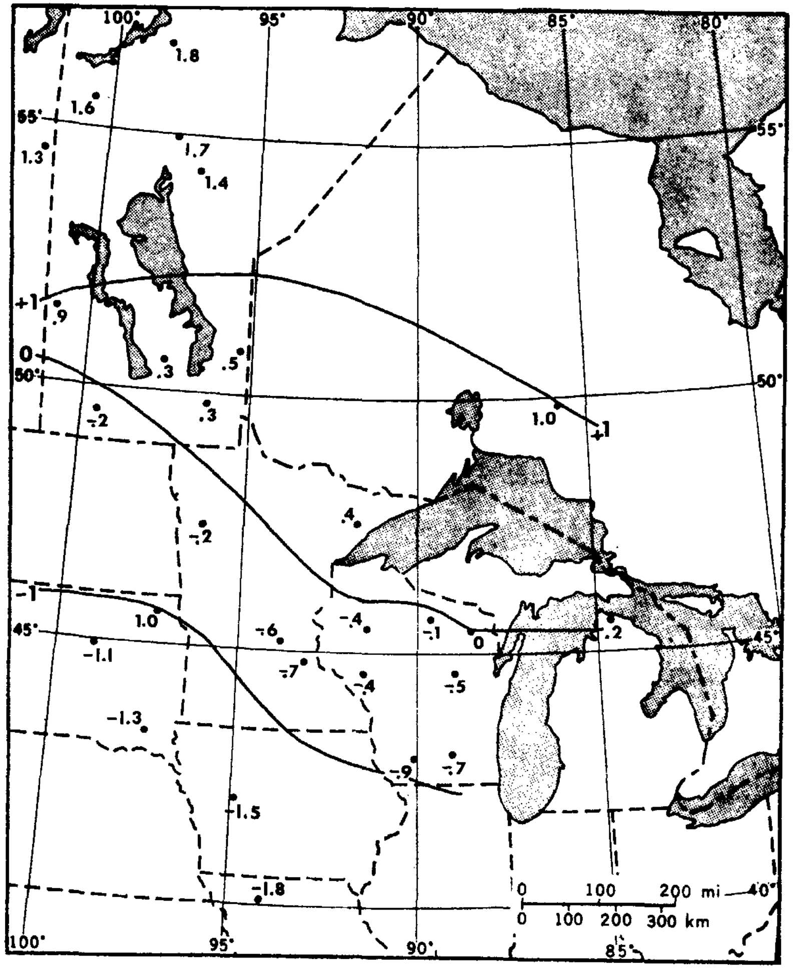
July air mass frequencies

	mT	cT	Ps	Pn	A
First	77	58	78	95	77
Second	13	15	16		8
Third		4		1	4
Fourth	1	3			
Fifth					
Total	92	81	95	96	89

Air mass durations

	mT	R	Ps	Pn	A
First	81	80	44	67	87
Second	1	2	42	1	4
Third	1	2		17	2
Fourth	5			1	1
Fifth					
Total	88	84	86	86	94

[a] Blank spaces indicate values of less than 1%.



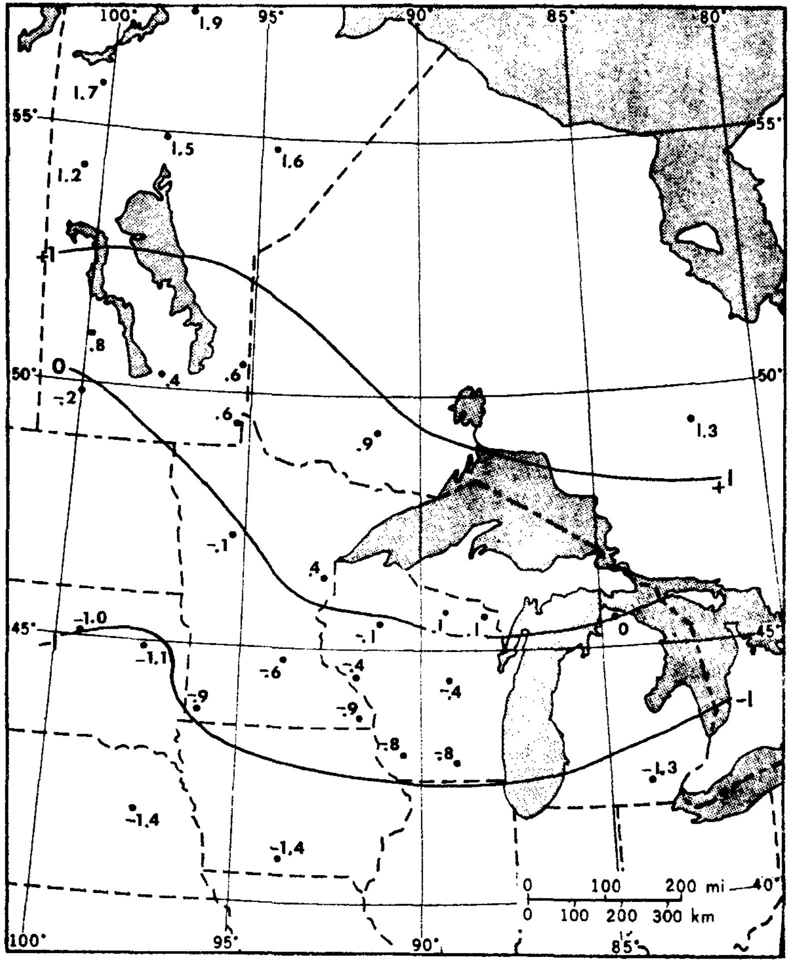


FIG. 12 (left). First canonical variate, u_1, with air mass durations as the climatic variables, REG-28.

FIG. 13 (right). First canonical variate, u_1 with air mass durations as the climatic variables, REG-30.

FIG. 14 (left). Second canonical variate, u_2, with air mass durations as the climatic variables, REG-28.

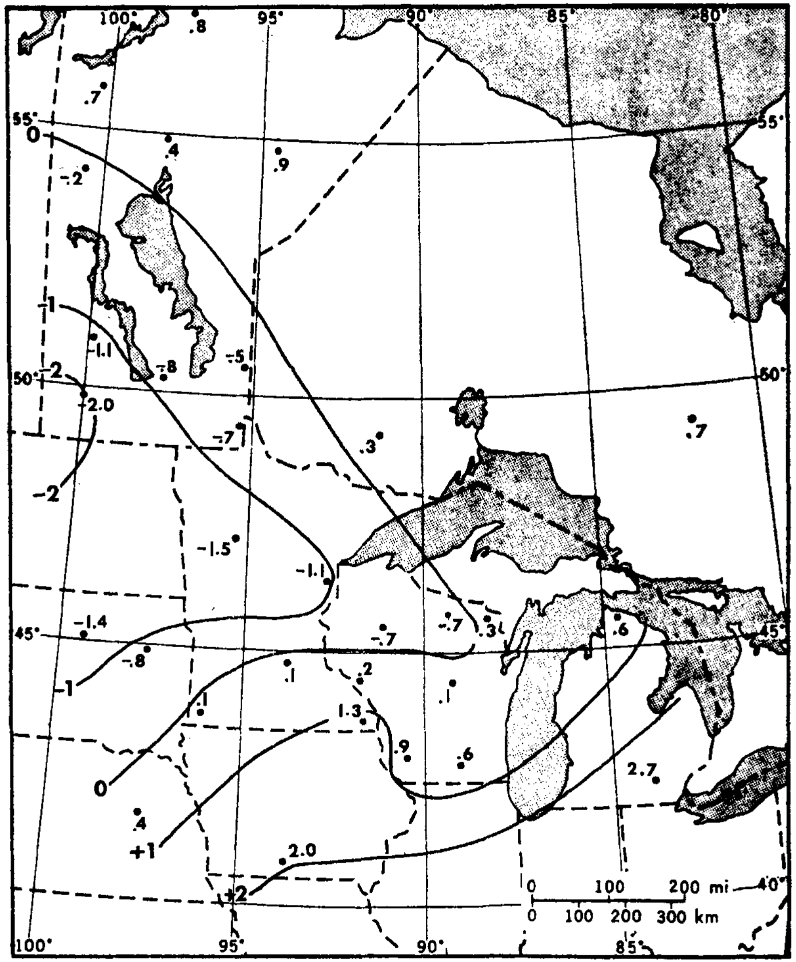


FIG. 15 (right). Second canonical variate, u_2, with air mass durations as the climatic variables, REG-30.

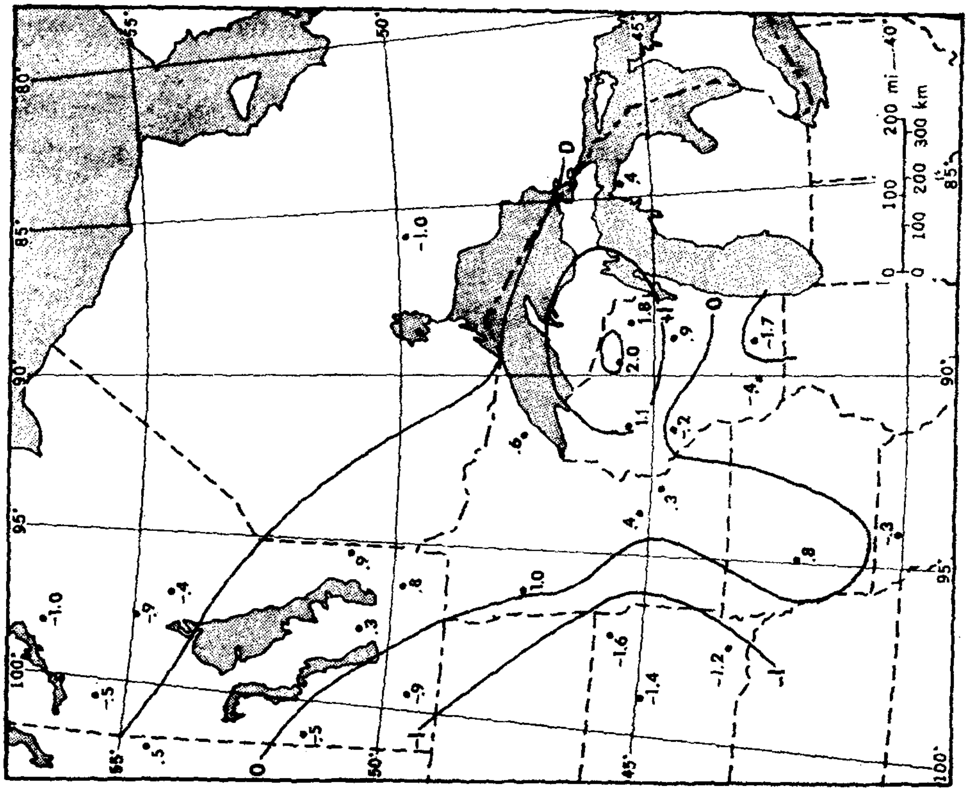


FIG. 16 (left). Third canonical variate, u_3, with air mass durations as the climatic variables, REG-28.

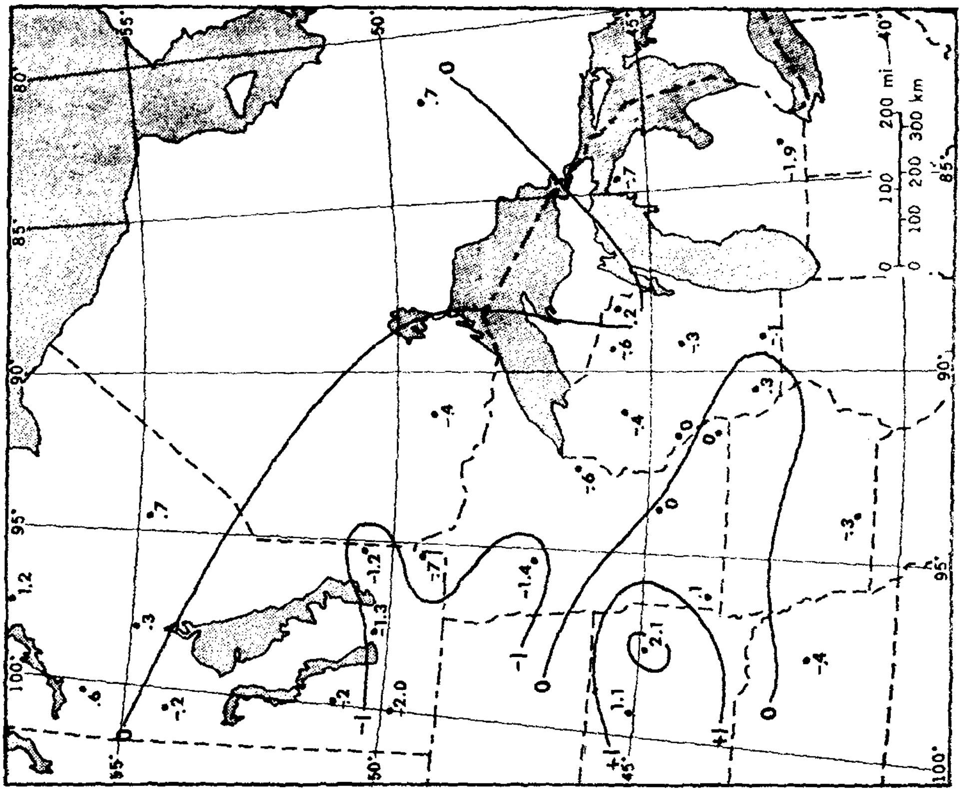


FIG. 17 (right). Third canonical variate, u_3, with air mass durations as the climatic variables, REG-30.

fied number of canonical variates comprise the transfer functions and are given in Table 4. For each climatic variable, these coefficients show the relative weighting of the various independent variables (pollen type plus latitude).

Test of Transfer Functions

In order to determine the accuracy of the chosen set of transfer functions, they were applied to the selected set of independent modern pollen samples, REG-25. The deviations of each estimated climatic variable from the observed value were calculated and plotted on maps. These calculations require that the absolute values of the climatic variables be derived first. This task is accomplished by using Eq. A.7, $\underline{\hat{Y}} = \beta^* X$, derived in the Appendix, to transform standardized values of the pollen variables into the set of standardized climatic values. The sample-mean and the sample-standard-deviation derived from REG-34 were used to standardize the variables. The standardized climatic values are then translated into absolute values in an inverse of the process of standardization. The deviation of each climatic variable at each site is then calculated by the following equation:

$$ {}_nY^*_q - {}_nY^*_q = {}_nG_q = (g_i), $$

where g_i are n by 1 column vectors ($i = 1, \ldots, q$) and consist of the deviations of a given variable at each site in REG-25.

Analysis of maps of the deviations of each variable reveal whether any systematic bi-

TABLE 4

CANONICAL REGRESSION FROM REG-34 COEFFICIENTS DERIVED FROM REG–34 (TRANSFER FUNCTIONS)

	Independent variables								
Dependent variables	*Pinus*	*Picea*	*Betula*	*Quercus*	*Acer*	*Carya*	*Juglans*	Chenopodiaceae	Latitude
Standard climatic variables									
P–PE	.54	.78	.41	.40	.11	−.02	−.07	−.20	−.64
Pg.s.	.46	.43	.17	.34	.04	.06	−.08	−.06	−1.24
D.D.	.02	−.20	−.15	.02	−.05	.07	.03	.09	−.17
Sun	−.42	−.87	−.17	−.37	−.16	−.01	−.06	−.22	−.26
Snow	.46	.82	.27	.38	.13	−.00	.01	.04	−.13
G.S.	−.01	−.22	−.16	−.01	−.05	.07	−.02	.08	−.61
T	−.13	−.41	−.23	−.11	−.08	.06	.01	.09	−.46
Air mass durations									
mT	.07	.06	.21	.32	.21	−.09	.20	.36	−.53
R	.05	.10	.15	.40	.18	−.04	.15	.40	−.60
Ps	−1.64	−1.95	−.68	−1.77	−.62	−.14	−.14	−1.95	−.20
Pn	.41	.50	.04	.26	.03	.10	−.10	.29	.43
A	.63	.76	.13	.50	.10	.12	−.09	.55	.47
July air mass frequencies									
mT	.34	.26	.10	.68	.24	.05	.30	.75	−.31
cT	.40	.35	.13	.74	.26	.07	.29	.80	−.26
Ps	−.93	−1.36	−.40	−1.09	−.43	−.19	−.07	−1.03	−.41
Pn	.26	.53	.14	.14	.07	.06	−.14	.07	.39
A	.73	1.10	.32	.82	.32	.15	.02	.75	.39

ases exist in the estimation of the climatic variables. In some instances, biases seem quite apparent. For example, the charts of the errors in the growing-season precipitation and the snowfall show a mesoscale pattern of negative deviations (underestimates) in northern Wisconsin (Fig. 18 and 19). This pattern results primarily from the higher elevation of this area and the presence of Lake Superior immediately to the north. Both the snowfall and the growing-season precipitation are enhanced by these topographic factors. A correction factor may be in order when values of these climatic variables are reconstructed at sites in this region (see descussion in the next section).

The charts of the error fields of the air mass durations also show some patterns, though they are less striking than the above-mentioned patterns. The slight biases in the air mass duration fields may result from the difference in time between the period of pollen accumulation (into the 1960's) and the period of the climatic records (the 1930's) (Webb, 1971).

In order to check the precision of the transfer functions, a set of 15 closely spaced sites from central Wisconsin was used. These sites include the three sites comprising point 49 on Fig. 1 and numbers 62–73 in Table 1 which are located just to the north and south of point 49. Because these samples provide 15 independent observations of essentially the same climate, the root-mean-square errors derived from the average calculated climate for these sites are a rough estimate of the precision of the transfer functions. Table 5 presents the values of these root-mean-square erors and reveals that in Wisconsin the transfer functions can estimate the July mean temperature within 0.6°C and the precipitation during the growing season within 2.0 cm. The root-mean-square errors of each variable provide a minimum value for the errors of estimate involved in deriving past climatic values from spectra of fossil pollen.

APPLICATION OF THE TRANSFER FUNCTIONS

The Fossil Pollen Data

In order to test the methodology developed in this paper, the transfer functions were applied to three sites of fossil pollen data. As shown in Fig. 1, Kirchner Marsh (Wright *et al.*, 1963) in east central Minnesota lies near the border of prairie and de-

TABLE 5

Error Estimates for each Climatic Variable

	Standard climatic variables						
	P-PE	Pg.s.	D.D.	Sun	Snow	G.S.	T
Root mean square error	60 mm.	20 mm.	183 d.d.	26 hr.	53 cm.	8.1 days	0.5°C

	Air mass durations				
	mT	R	Ps	Pn	A
Root mean square error (in months)	0.4	0.6	0.5	0.2	0.4
	Air mass frequencies				
	mT	cT	Ps	Pn	A
Root mean square error (in %)	1.4	0.8	2.9	1.8	1.4

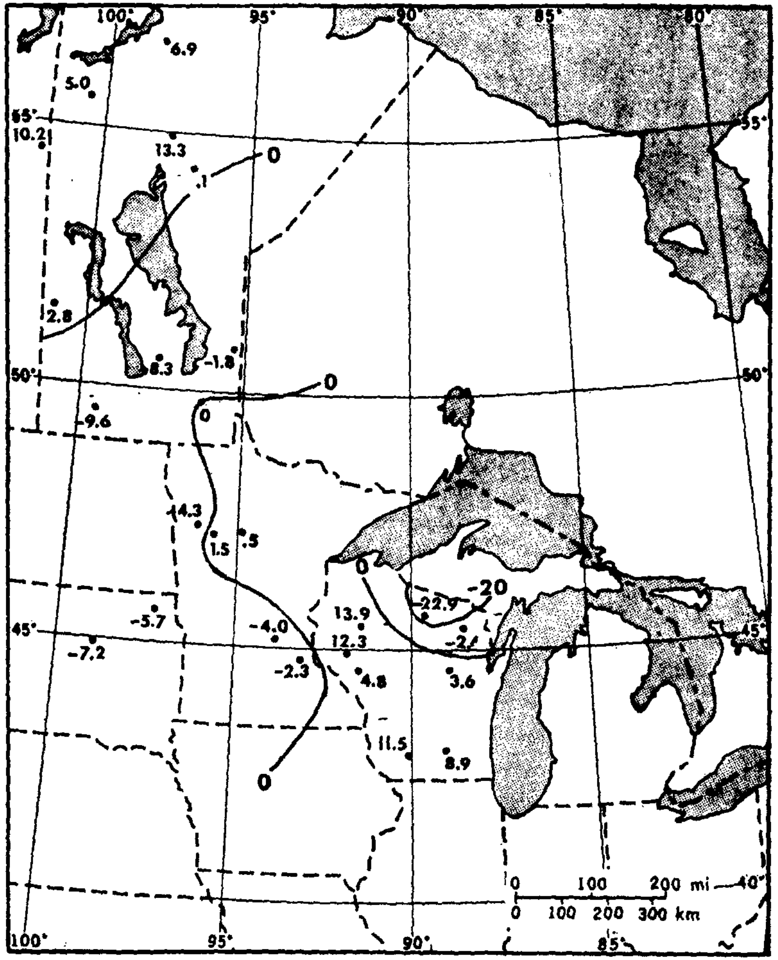


Fig. 18 (left). Error estimates for the annual snow fall, REG-25, in inches.

Fig. 19 (right). Error estimates for the growing season precipitation, REG-25, in inches.

ciduous forest that runs northwest–southeast across Minnesota. Disterhaft Farm Bog (West, 1961) is just north of the "tension zone" (Curtis, 1959), the boundary between the deciduous and conifer–hardwood forest in central Wisconsin. The third site, Lake Mary, is located in the middle of the conifer–hardwood forest in northern Wisconsin. The pollen at Kirchner Marsh was analyzed by T. C. Winter (Wright *et al.*, 1963); at Disterhaft Farm Bog by R. G. Baker (unpublished data); and at Lake Mary by T. Webb III (1971). The standard procedure (Faegri and Iversen, 1964) of acetolysis and HF treatment and slide-mounting in silicone oil was followed in processing the pollen at KM, DFB, and LM. At least 300 grains were counted at each of the levels in the cores.

Instead of using one or two sites to test the transfer functions, three sites were chosen because the consistency of the results can be checked simply. Their different locations reveal whether Pacific air predominates more in the west, Arctic air more in the north, etc. The use of more than one site also permits the gradients between the sites to be estimated and the changes in these gradients to be indicated.

Scaling the Results

The procedure for applying the transfer functions to the fossil spectra is the same as the one used to apply the transfer functions to the independent set of modern pollen. The spatial sample-means and spatial sample-standard-deviations for the pollen variables in REG-34 are used to standardize the fossil pollen data. These are transformed by the transfer functions into climatic estimates in standard-deviation units. The spatial sample-mean and spatial sample-standard-deviations of each climatic variable are then applied in order to scale each of the estimates in appropriate units of inches, degrees, or days.

Figures 20–22 present some of the results of these operations on the fossil data from each of the cores. Examination of these figures reveals that at any level the five air mass duration values all sum exactly to 12 (and, were the curves of air mass frequencies portrayed, the frequency values would total 100%). The method of scaling these variables therefore meets these constraints.

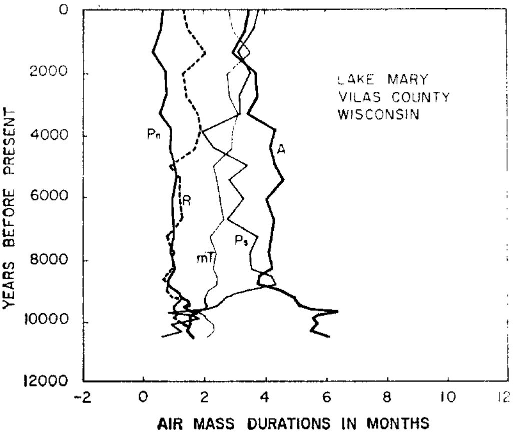


FIG. 20. Reconstructed sequence of the duration of five air masses for Lake Mary: maritime Tropical (mT), Return Polar (R), Pacific-south (Ps), Pacific-north (Pn), and Arctic (A).

Two inconsistencies are apparent in these data. The values of the climatic variables derived from the top sample in each core do not equal the observed values for the respective variables (Table 6), and undefined values are calculated for certain variables, e.g., minus 2 months of maritime Tropical air. This second problem may arise in part because too arbitrary a division of the air masses was used. Combining the two western air masses and the two southern air masses reduces the number of air mass duration variables from five to three and eliminates the negative values (see Figs. 23–25). These variables may be better represented in this composite form in this paper. Interpretations of the particular meaning of the negative values that do appear are given in the description of the results.

The first inconsistency is not unexpected because the transfer functions produced similar errors when applied to modern spatial samples (REG-25). For most variables, the discrepancies lie within the limits

TABLE 6

Comparison of the Climatic Estimates from the Topmost Sample in a Core with Modern Observed Values at that Site

	Kirchner Marsh		Disterhaft Farm Bog		Lake Mary	
	obs.[a]	*ca.* 250 B.P. recon.[b]	obs.	*ca.* 500 B.P. recon.	obs.	Present recon.
Air mass durations (in months)						
mT	3	2.8	3	3.4	3	2.8
R	2	1.4	2	1.3	2	1.3
Ps	4	4.8	3	5.2	3	3.8
Pn	0	0	0	.1	0	.7
A	3	3	4	2.0	4	3.4
July air mass frequencies (in %)						
mT	14	12	13	14	4	7
A	8	4	10	5	14	11
Ps	63	65	56	66	49	59
Pn	15	18	15	11	26	23
cT	2	1	—	.3	—	1
Standard climatic variables						
P-PE (in mm)	−125	25	100	38	300	183
Pg.s. (in mm)	478	470	460	495	523	462
D.D. (in degree days)	4175	3918	4400	4205	3350	3233
Sun (in hr)	2525	2469	2500	2562	2300	2375
Snow (in mm)	1190	1270	1040	1220	2030	1450
G.S. (in days)	140	137	130	144.5	102	119
T (in °C)	22.2	21.8	22.5	22.4	18.9	19.9

[a] obs.—observed.
[b] recon.—reconstructed.

of three root-mean-square errors. When they do not, these "errors" may result, as discussed earlier, from the different times of accumulation of the climatic and pollen data. At two of the sites, KM and DFB, in fact, the difference in the time between when the pollen accumulated and when the climatic values were measured is quite large. The top sample in the core from DFB dates from *ca.* 500 to 600 B.P.,[5] and the top sample from KM accumulated about 250 years ago.[6] In both instances, the top few was applied to the climatic time series. The centimeters of the core were lost when it was collected.

For instance, the higher then observed values of Pacific-south air calculated at DFB may well be an accurate reconstruction of the climate of the Pacific episode that extended from 1200–1550 A.D. This was a time of increased penetration of Pacific air into the Midwest during the summer (Baerreis and Bryson, 1967). The period around 1700 A.D., when the pollen at KM accumulated, was similar climatically to today, especially in summer (Fritts *et al.* 1971).

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[5] As explained in the next section, this date was calculated by linear interpolation between the topmost dated level and the surface which was assummed to have a date of *ca.* 1950 A.D.

[6] The top sample at DFB comes from 50 cm below the surface; and at KM, from 30 cm below the surface.

The surprising agreement between the calculated and observed values of the air mass frequencies may record this fact.

The markedly lower estimates of the growing-season precipitation and the snowfall at LM are consistent with their error patterns discussed earlier. These errors result from the higher elevation of this area of Wisconsin and its proximity to Lake Superior, two features of the landscape that have remained unchanged during the postglacial and not well-accounted for in the interpretation of the basic climatic data. Their influence can be accounted for by changing the scale of both climatic measures. The appropriate site-correction is achieved by increasing each estimate by the percentage the calculated values for the surface sample at LM differed from the observed value. This correction is used in plotting the values of the growing-season precipitation for LM in Fig. 8 and in recording the values of both these variables in Table 7. (The corrected values are given in parentheses in Table 7.)

Radiocarbon dates provide the vertical scale for the curves in Figs. 22–28. These dates are indicated in Fig. 2, and the points between consecutive dates are positioned by linear interpolation. Although the points are placed as well as this approximation permits, all are only roughly located in time because the sedimentation rate may be nonlinear, especially near the bottom of a core, and each radiocarbon date may contain a variety of errors. Counting errors that arise mainly from the random release of radiation from the sample are ±300 years for each sample. Inter- and intralaboratory differences in dates are also significant. Kim (1969) calculated these errors to be about 5%. The position of each point is therefore not absolutely fixed along the vertical axis.

DESCRIPTION OF THE RESULTS

Because palynologists commonly zone their pollen diagrams in order to simplify the description of their results, a similar practice zonal boundaries were drawn at the points of major change in the reconstructed climatic curves. Preference was given to the air mass duration curves in marking the zones because these variables reflect the changes in the general circulation of the atmosphere. It is these changes that dynamic climatologists generally recognize as representing climatic change.

Table 7 gives a brief description of each of the pollen zones in terms of the major pollen contributors for each of the three sites. Along with the description of the pollen data, the table presents a summary of the climatic values within each zone. In this table, the composite air masses are labeled S for maritime Tropical plus Return Polar, W for Pacific-south plus Pacific-north, and N for Arctic. These values represent "mean values"[7] for each variable during each of the climatic zones as indicated on Figs. 23–25. Good agreement exists between the dates of the pollen zonal boundaries (Fig. 2) and the dates of climatic change,[8] but as expected the transfer functions acted to amplify or to dampen some of the changes recorded in

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[7] These "mean values" were determined by visual examination of the derived curves for each variable. The mean values are designed to reflect the equilibrium values of each variable. Its size during periods of transition from one equilibrium level to the next were, therefore, not used in these calculations. (The implicit assumption behind this method of summarizing the data is that the climate assumes a certain equilibrium state over a certain period of time and then shifts to a different equilibrium state—Bryson *et al.* [1970].) Because an objective method for distinguishing equilibrium values from transition values had not yet been developed, this subjective procedure for summarizing the results during each episode had to be used.

[8] In the analysis of the results, the time when a new climatic equilibrium is reached is assummed to be sooner than the climatic data derived from the pollen may show. This assumption is based on the idea that a lag error is contained in time series of climatic variables derived from pollen data (Cole, 1969; Bryson *et al.*, 1970). This phenomenon results from the lag in the response of the vegetation to changes in the climatic-forcing function. The exponential shape of many of the derived climatic curves suggests this sort of

the pollen curves. Certain changes are climatically more significant than others.

At each of the sites, the decrease in spruce pollen was reflected in the climatic time series as a time of major change. The more recent shift from the prominence of pine pollen at DFB to prominence of oak pollen is also registered in the climatic estimates (Fig. 24). The later zones (described by West, 1961) at 5400 and 3000 B.P. are not apparent in the climatic data, primarily because the pollen types (grass and sedge) used to delineate these zones (see Fig. 2) were not included in this study. However, because these zones may have only local rather than regional significance (Baker, personal communication), no climate meaning may be connected to them. The several late-glacial zones of West are also not clearly defined in the climatic data, partly because more widely spaced samples were used in this study than in West's. For this reason, Baker (personal communication) finds West's zones 1–4 more subtly designated in his diagram than in West's diagram (1961). These changes in pollen are small even in West's diagram in comparison with the pollen changes at the beginning of and throughout the postglacial.

At KM, all the changes in the pollen profiles are well-recorded in the climatic time series. The change at 12,050 B.P. is not a major one in the climatic time series, but cooler conditions are definitely indicated just after this time and support the interpretation of the pollen change given by Wright *et al.* (1963).

At LM, all the major changes in pollen are also recorded by the climatic profiles except for the change at 8500 B.P., when white pine pollen replaces red and/or jack pine pollen. Because distinction of the pine types was not available for all the modern pollen data of this study, there is no possibility for the climatic curves to reflect this change. As at KM, a minor change in the pollen about 7400 B.P. is amplified in the estimated climatic time series.

In the description that follows, the climatic history of central Minnesota and Wisconsin is traced by means of the composite of climatic variables estimated. Much redundancy exists within the reconstructed climatic data, e.g., time series of the air mass frequencies resemble the time series of air mass durations, and the curves for degree days or length of growing season parallel the curves of July mean temperature. For this reason, the climatic events are discussed in terms of only a few of the variables, and the complete depiction of all variables is relegated to Table 7.

The Late Glacial (15,000–ca. 11,300 B.P.)

General character of the climate. The records in two of the cores, KM and DFB, begin during the late glacial episode and indicate a colder, moister, cloudier[9] climate during this whole period (Fig. 26). The temperature in July was as much as 4.4°C below its currently observed value.

These lower temperatures probably resulted from the dominance of "Arctic" air[10] during the summer and the shorter duration of maritime Tropical air in the region. Resultant air flow from the south predominated

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behavior (see the curve of the duration of Pacific air *ca.* 11,300 B.P. at DFB in Fig. 24).

This model of vegetation–climate interaction implies that the actual climatic changes occurred over much shorter periods than the derived climatic curves indicate. The longer the assumed lag in the pollen, the more rapid the implied change in climate. The model also implies that the date assigned a climatic change should be the date when the curves first indicate a shift toward a new value rather than the time when the new mean is first registered. The dates of the zonal boundaries on Table 7 were determined using the reasoning just outlined. The dates are therefore often slightly earlier than those given in the literature (Wright *et al.*, 1963; Bender *et al.*, 1971).

[9] That is, there were fewer hours of sunshine.

[10] Though the character of "Arctic" air in the late glacial must have been somewhat different from that in the present (see Bryson and Wendland, 1967).

TABLE 7

SUMMARY OF THE POLLEN AND CLIMATIC ZONES

Lake Mary

Time (in years B.P.)	Designated pollen zones (Webb, unpublished ms.)	Main pollen contributors	Air mass durations (in months)			July air mass frequencies (in %)					Standard climatic variables						
			S	W	N	mT	cT	Ps	Pn	A	Pg.s. (in mm)	Snow (in mm)	Sun (in hr)	P-PE (in mm)	T (in °C)	D.D. (in deg. days)	G.S. (in days)
0																	
2000	4	White Pine Birch Hemlock	4.5	4.0	3.5	8	—	57	23	12	450 (510)[a]	1420 (1990)	2370	150	20	3350	119
4000																	
6000	3	White Pine	4.0	3.5	4.5	10	1	54	22	13	460 (520)	1420 (1990)	2360	130	20.5	3450	125
8000																	
	2	Jack and/or Red Pine	3.0	5.0	4.0	7	1	60	22	10	460 (520)	1400 (1960)	2380	130	20.5	3400	125
10,000																	
	1	Spruce Jack and/or Red Pine	3.0	3.5	5.5	8	—	43	30	19	460 (520)	1780 (2490)	1950	240	19	3100	116
10,500(?)																	

Disterhaft Farm Bog

Time (in years B.P.)	Designated pollen zones (West, 1961)	Main pollen contributors	Air mass durations (in months)			July air mass frequencies (in %)					Standard climatic variables						
			S	W	N	mT	cT	Ps	Pn	A	Pg.s. (in mm)	Snow (in mm)	Sun (in hr)	P-PE (in mm)	T (in °C)	D.D. (in deg. days)	G.S. (in days)
0																	
2,000	8	Oak Pine															

6,000	6	Oak Pine															
8,000																	
10,000	5	Pine Oak	4.3	4.2	3.5	13	–	61	17	9	530	1780	2440	160	68.0	4230	144
12,000	3–4	Spruce	4.0	2.5	5.5	8	–	36	34	24	530	1970	1770	380	66.5	3350	121
14,000																	
15,600	1–2	Spruce	4.5	1.0	6.5	8	–	24	39	29	540	2170	1570	480	65.0	3200	115

Kirchner Marsh

Time (in years B.P.)	Designated pollen zones (Wright *et al.* 1963)	Main pollen contributors	Air mass durations (in months)			July air mass frequencies (in %)					Standard climatic variables						
			S	W	N	mT	cT	Ps	Pn	A	Pg.s. (in mm)	Snow (in mm)	Sun (in hr)	P-PE (in mm)	T (in °C)	D.D. (in deg. days)	G.S. (in days)
0																	
2000	C-c	Oak, Pine Sedge	4.0	5.0	3.0	14	1	64	14	7	470	1250	2500	30	21.5	3900	137
4000		Oak	5.5	4.5	2.0	16	2	64	12	6	440	1120	2550	−50	22.0	3900	138
6000	C-b	Oak, Herbs	4.0	6.0	2.0	14	2	69	11	4	420	1030	2600	−150	22.5	3950	140
		Herbs	3.5	7.0	1.5	11	2	75	10	2	410	1000	2650	−220	22.5	3950	139
8000	C-a	Oak, Elm Herbs	4.0	6.5	1.5	14	2	70	11	3	430	1080	2580	−130	22.0	3850	137
10,000	B	Pine, Elm, Oak Birch, Alder	3.0	4.5	4.5	13	–	61	17	9	460	1250	2480	50	21.5	3800	134
	A-b	Spruce															
12,000	A-a	Spruce, Ash	4.0	3.0	5.0	6	–	40	32	21	490	1870	1850	350	19.0	3070	114
13,500	K	Spruce, Herbs	4.0	–	8.0	7	–	20	42	32	520	2200	1470	480	18.0	2880	108

[a] Corrected values are given in parentheses. See text for discussion.

for 4 months, probably in summer and fall, and indicates that the front between westerly streamlines and southerly streamlines lay to the north of both sites during these seasons. The combination of frequent "Arctic" air in July and resultant southerly flow implies the meeting of contrasting air masses in this area. The cloudy, rainy conditions, associated with frontal zones, are consistent with this picture. More snow also fell during the cold season.

These are all climatic conditions consistent with the presence of a high proportion of spruce pollen except for the greater amount of precipitation during the growing season. The prominence of spruce pollen at lower latitudes than today and the presence of deciduous trees, e.g., oak, not found in comparable quantities at sites in the boreal forest today (Wright *et al.,* 1963) may be in part indicative of the moister conditions. (See later discussion, however.)

In partial support for the reconstructed picture of cooler, moister summers during the late glacial, the snail evidence derived from loess deposits in Iowa dated as 18,000–13,000 B.P. is indicative of these same conditions (Leonard and Frye, 1954).

Negative durations of Pacific-south air appear during the early portion of the late glacial (Figs. 21 and 22). These undefined values are probably an indication of just how different the climate was during this episode. Both sites were close to the glacial boundary at this time (see Fig. 2 in Bryson *et al.,* 1970). The high mountain of ice to the north certainly changed the flow patterns and characteristics of the various air masses. Arctic air must have been quite different from today (Bryson and Wendland, 1967). As discussed earlier in this section, a better picture of the circulation may be gained by combining Pacific-south and Pacific-north air to show resultant westerly flow. The exact character of this composite air mass during the late glacial is hard to assess but it may have been moist and cool, because it crossed forested lands in the Great Plains, some parts of which were also receiving meltwater from the glacier. This air was also undoubtedly colder aloft when it reached the eastern Rockies.

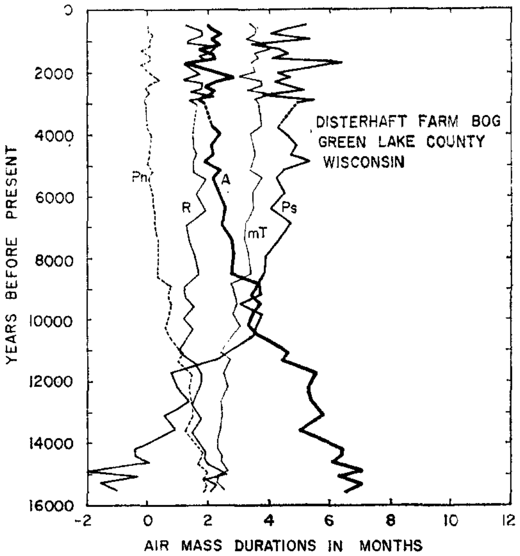

FIG. 21. Reconstructed sequence of the duration of five air masses for Disterhaft Farm Bog.

The only major changes during this period date from *ca.* 14,800 B.P. at DFB and

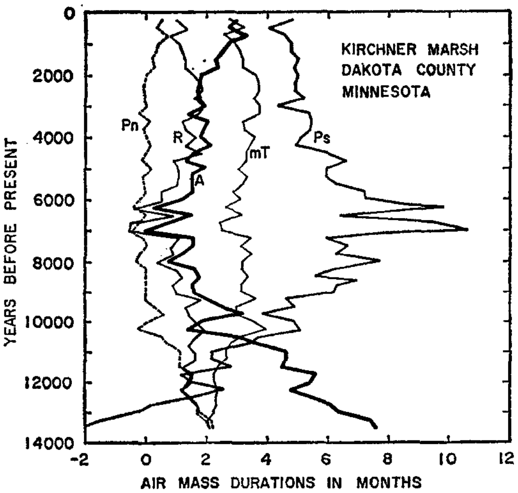

FIG. 22. Reconstructed sequence of the duration of five air masses for Kirchner Marsh.

from before 13,000 B.P. at KM. Much colder and moister weather is indicated for the period from 15,600 to 14,800 B.P. or 13,500 B.P. A warming of 1.1°C in July occurs after this time (Fig. 26), and the proportion of Pacific air increases. These changes may reflect the end of the Mankato–Port Huron advance, which dates from this time period (Wright and Ruhe, 1965; Farrand *et al.,* 1969). A less pronounced change toward cooler conditions is evident at KM about 12,000 B.P., as noted earlier.

Change at the end of the late glacial. The transition at the end of the late glacial is the most marked of all transitions that were reconstructed. Among the standard climatic variables, those related to temperature show a large increase, e.g., the length of the growing season, degree days, moisture stress, and July mean temperature (Table 7). The main change in the circulation is for Pacific-south air to prevail in winter and to become most frequent during July (Table 7, Fig. 22). The amount of cloudiness declines with the rise in dry westerly flow, and the snowfall decreases (Table 7). The length of the summer season (duration of maritime Tropical air) also increases by 1 month (Table 7). These changes are consistent with the decline of spruce pollen at each of the sites.

The date for this break in climate appears to fall within a few centuries of 11,300 B.P. in the data at hand. The shift at DFB is earlier than this date, while the change at KM is later (e.g., see Figs. 24 and 25). As previously discussed, the apparent difference in the timing of a climatic event reconstructed from the two sites may be rendered indistinguishable by the size of errors in dates this old, the nonlinearity of the sedimentation rate at this level, and the discrepancies in dates established by different laboratories (Wendland and Donley, 1971). More field work, analyses, and radiocarbon dates are needed in order to discern the exact sequence of events around this time period.

The Postglacial (11,300–present)

At the beginning of the postglacial, the climates at KM and DFB were warmer than before (by 3.3°C in July, Table 7, Fig. 26), but the amount of rain during the growing season remains the same (Fig. 26). Pacific air predominates during the winter season (Figs. 21 and 22) and the winters are less snowy and cloudy (Table 7). The conditions are consistent with the rise of birch and pine pollen in the pollen record at each of these sites.

The picture is quite different at LM, where pollen began to accumulate between 10,500 and 10,000 B.P., and both spruce and pine pollen predominate. There Arctic air prevails 2–3 months longer than at the southern sites, and the winters are snowier (Table 7, Fig. 23). The north–south gradients of these variables in Wisconsin are steeper than their gradients today.

LM lies, at this time, within 100 miles of the southern border of the glacier (Bryson *et al.,* 1969). The chillier, snowier climate reconstructed at LM is likely a part of a mesoscale climate that developed just beyond the glacial boundary. This picture is supported by the work of Smith (1962) and

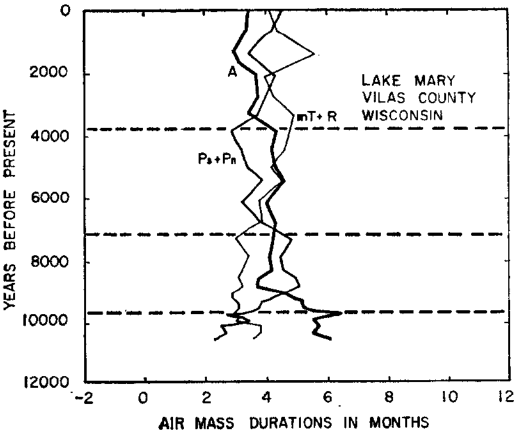

FIG. 23. Reconstructed sequence of the duration of composite air masses for Lake Mary: Pacific (Ps + Pn), Southern (mT + R), and Arctic (A).

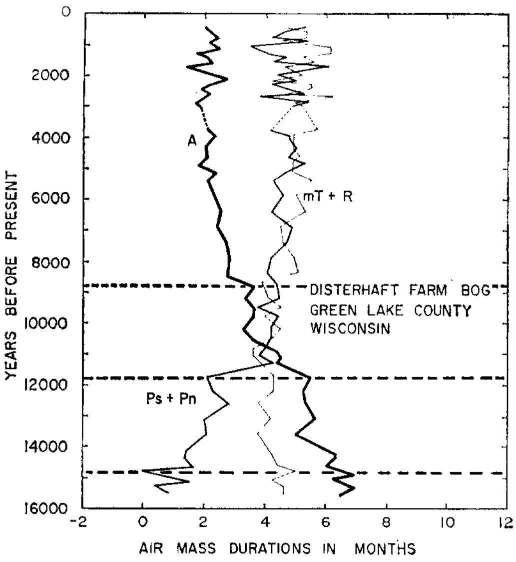

FIG. 24. Reconstructed sequence of the duration of three composite air masses for Disterhaft Farm Bog.

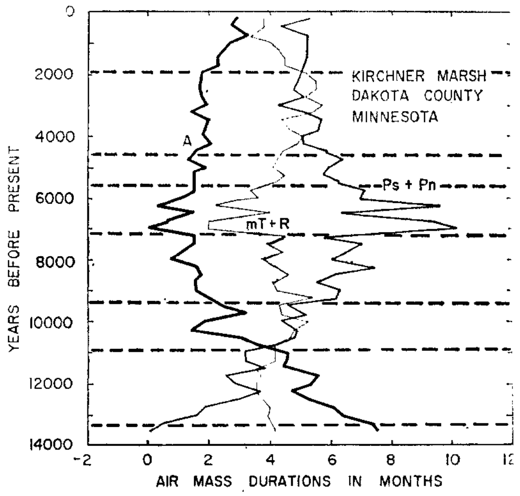

FIG. 25. Reconstructed sequence of the duration of three composite air masses for Kirchner Marsh.

of Moran (personal communication) that indicate that a zone of colder conditions lay within 100 miles of the glacial border.

About 9500 B.P., changes are evident at both LM and KM. At the first of these sites, the resultant flow of Pacific air increases to replace Arctic air during 2 months (probably in late winter), and the July mean temperature rises by 1.1°C (Table 7, Fig. 23). The difference in moisture stress and dominance of Pacific air between northern and central Wisconsin is less than during any other time during the Holocene (Table 7, Fig. 26). These changes are associated with a spruce decrease and pine increase in the pollen record at LM. The pollen changes probably indicate the presence of a mixed conifer–hardwood forest in that region with a predominance of pines (Webb, unpublished manuscript).

At the same time, the east–west gradient in precipitation, moisture stress, and the duration of Pacific air steepens between KM and DFB (Table 7, Fig. 26). This pattern remains prevalent until *ca.* 4700 B.P. and becomes more evident after 7200 B.P.

About 8600 B.P., a change in climate occurs in central Wisconsin and is associated with an increase in oak pollen and decreasing pine pollen. This shift toward deciduous forest conditions accompanies an increase in maritime Tropical air by one month at the expense of Arctic air (Table 7). The late-spring frontal boundary between these air masses (Fig. 7) probably shifted to the north of DFB a month earlier than previously. The rain zone along this front was therefore probably shifted to the north of this site.

About 7200 B.P., the flow of Pacific air decreases and that of maritime Tropical air increases at LM. Just the opposite change occurs at KM, where there is a decrease in tree pollen and an increase in herb pollen, indicating the begining of the prairie period at that site. Less precipitation falls during the growing season, and Pacific air persists longer, probably into the spring season (Figs. 6 and 7). The flow of northerly air, which prevails in spring, decreases; and the flow of southerly air also decreases. In effect, the dry western air may have replaced the more humid air from the south, which is the main source of moisture in this region.

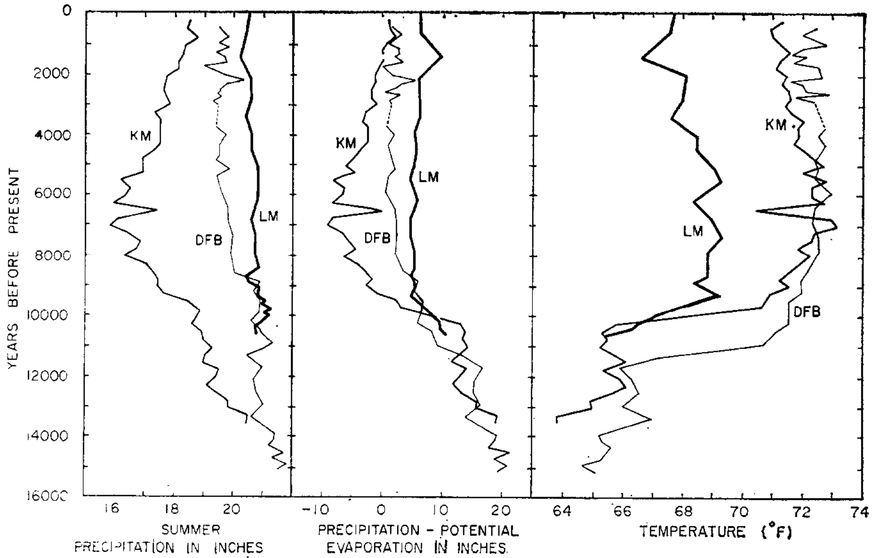

FIG. 26. Plots of the reconstructed values of the precipitation during the growing season, the precipitation minus potential evaporation, and the July mean temperature for the three sites of fossil pollen.

This change may have resulted from a shift to a stronger zonal index across North America. The change in spring implies that the wedge of Pacific air persisted longer than during other episodes.

The gradient in rainfall and moisture stress that developed earlier between Wisconsin and eastern Minnesota steepened. This occurrence is consistent with the above inference of a stronger zonal index (see Map 8 in Bryson *et al.*, 1970).

This period is the one of maximum dryness at KM, and the climate was similar to that now found in eastern South Dakota (see Table 8). At this same time, the pollen data at KM indicate the maximum extent of prairie conditions in Minnesota (Wright *et al.*, 1963). It is also a time when there are abrupt oscillations in the time series of several variables at KM. These oscillations and other features of the reconstructed climatic values, e.g., negative durations of Arctic air, seem to reflect noise[11] in the pollen data. Independent macrofossil analysis at KM by Watts and Winter (1966) indicates that between 7200 and 6200 B.P. the lake level was lower and periodic fluctuations occurred in the lake level. Evidently the change in the macroclimate drastically altered the local environment, and this change may be reflected in the noise contained in the climatic reconstructions.

Determination of the exact amount that the oscillations in the climatic variables reflect noise in the data must await later investigations when climatic time series are extracted from other pollen profiles in this area. Comparison of these time series with those at KM will reveal which changes are regional and which are local. The former can be identified as significant macroclimatic events and the latter as representative of noise in the data.

The reconstructed climatic time series from KM register two changes in climate about 5500 B.P. and later about 4700 B.P. There is a decrease in the duration of Pacific air and a rise in Arctic and southerly flow (Fig. 25). Oak pollen increases to replace the dominance of herb pollen during the

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[11] In this context, "noise" means fluctuations in the pollen spectra which yield apparent fluctuations in climate but are not indications of change in the macroclimate.

TABLE 8

Comparison of Reconstructed Values at Kirchner Marsh with Modern Observed Values at Two Locations in Eastern South Dakota

	7200–5500 B.P.	Huron 44°N 98°W	Pickerel Lake 46°N 97°W
Air mass duration (in months)			
mT	3.0	3.0	3.0
R	0.5	1.0	1.0
Ps	7.0	6.0	6.0
Pn	0.0	0.0	0.0
A	1.5	2.0	2.0
Standard climatic variables			
P-PE (in mm)	−220	−510	−360
Pg.s. (in mm)	410	350	360
D.D. (in deg. days)	3950	4197	3801
Sun (in hr)	2650	2800	2700
Snow (in mm)	1000	890	910
G.S. (in days)	139	137	135
T (in °C)	22.0	23.9	22.8
Air mass frequencies (in %)			
mT	11	14	13
cT	2	5	9
Ps	75	76	75
Pn	10	5	1
A	2	0	2

first change, and herbaceous pollen decreases during the second. The precipitation increased at KM and the temperature decreased (Fig. 26). This change in temperature parallels the decrease in temperature that began earlier at LM. The east–west moisture gradient between the sites in Minnesota and Wisconsin was greatly reduced by the changes (Table 7, Fig. 26).

About 3800 B.P. at LM, the duration of westerly air increased 1 month and the duration of Arctic air decreased by a comparable amount. This change probably indicates that the spring front between these two air masses (Fig. 7) shifted to the south of LM a month earlier, in accord with the general southward shift of climatic zones recorded by fossil sites at the northern edge of the boreal forest (Bryson *et al.*, 1965).

The reconstructed time series for KM show a rise in the duration of Arctic air and decrease in maritime Tropical air after 2000 B.P. (Fig. 22). The temperature and moisture stress also decrease. These changes result in reconstructed values in the climatic variables that indicate conditions more like those about 10,000 B.P. than the intervening episodes. The exact meaning of this indicated climatic change is unclear, however, because it is associated with an increase in pine pollen. This event has no parallel in other cores from this region, e.g., Lake Carlson (Wright *et al.*, 1963), Rutz Lake (Waddington, 1969) or other lakes (McAndrews, 1968), and was not used to indicate a pollen zone (Wright *et al.*, 1963). The estimated climatic values indicate the expected type of climatic change for replacement of oak pollen by pine, but since this event is not regional, the climatic interpretation of macroscale changes may be incorrect.

Summary

In summary, two major climatic events are apparent in the estimated climatic time series. The first is the distinct change from the late glacial climate to that of the Holocene period that occurred about 11,300 B.P. During the late glacial, the reconstructed climates at DFB and KM are quite similar. Colder, snowier, cloudier, and moister conditions prevailed at both. The nature of the air masses was quite different from today, but the composite picture indicates more northwesterly flow than today with 4 months of southerly flow during the warmer season.

During the transition to the Holocene, Pacific-south became the prevailing air mass during winter, and the increase in July mean temperature was three times the size of any change in temperature during the Holocene. After 10,500 B.P., the pollen record at LM began. The earliest reconstructed climatic values for this site indicate the presence of a mesoscale climate determined by the proximity of the glacier to the north. About 9500 B.P., with further retreat of the ice sheet northward, however, this smaller-scale climatic pattern ceased to prevail in northern Wisconsin.

At the same time, the moisture gradient between KM and the Wisconsin sites began to steepen, with an increase in the duration of Pacific air at KM. This marks the beginning of the second major climatic event. From 9500 to 4700 B.P., there was increased flow of westerly air in central Minnesota associated with a 2-in. decrease in precipitation during the maximum penetration of westerly air about 7200 B.P. At this time the climate at KM resembled today's climate in eastern South Dakota. After this period, the amount of westerly flow decreases and the precipitation increases. The climate after 4700 B.P. has changed relatively little, although the estimated time series indicate cooler conditions in the last 2000 years.

DISCUSSION

Without measurements of climatic variables from the past, there is no exact means of confirming the climatic sequence reconstructed in this paper. The best alternative is to examine the climatic data and patterns derived from other studies of past climatic information to see if they confirm or deny the results of this paper.

For this purpose, the results described in this paper are compared to the postglacial climatic events and patterns in the Midwest that were constructed in three recent review papers (Wright, 1968, 1970; and Bryson and Wendland, 1967). Wright's two works include a brief discussion of temperature and precipitation changes and his 1968 paper suggests a possible change in the atmospheric circulation. Maps of past circulation patterns appear in the Bryson and Wendland paper. The discussion and results contained in these three studies are in a form that can be compared with the quantitative estimates derived in this paper. Most other papers examined contain comments on climatic change that are too general to be used for verifying the results of this paper. Two examples are papers by Lamb (Lamb *et al.*, 1966; Lamb and Woodroffe, 1970) that depict circulation patterns in the Northern Hemisphere for the postglacial and late glacial. The maps from these papers are unfortunately of too broad a scale to facilitate comparison of their results with those of this paper. The 1966 paper also contains a quantitative plot of the July mean temperature for the lowlands of central England during the postglacial. The magnitude of the changes in temperature in this figure (Fig. 1c in Lamb *et al.*, 1966) is comparable to that shown in Fig. 26. Since England experiences a maritime climate in which temperature changes are damped, the changes in the northern Midwest are probably not less than those shown in this paper.

For the Midwest, no quantitative time series of temperature and precipitation during the postglacial were found that could be compared to the results of this paper. The most specific comments concerning these variables were made by Wright (1968). Considering in part the pollen record at KM, he stated that the climatic curve showed maximum warmth and dryness about 7000 B.P., a gradual decrease until 4000 B.P., and a more rapid decrease since then. He also attributed the prairie advance from 8000 to 5000 B.P. to greater dryness in the area. The results of this paper are largely in agreement with this final comment, but show no trend in the combination of temperature and precipitation, which might be viewed in the precipitation minus potential evaporation (P–PE) curve (Fig. 26), to confirm the exact shape of his increasing and decreasing climatic curve; 7000 B.P. is the time of maximum warmth and dryness, but no increase in the rate of change of P–PE has occurred since 4000 B.P.

In part, this difference in the interpreted change in temperature and moisture arises because Wright incorporated the changes at Jacobson Lake (Wright and Watts, 1969) in his interpretation. Application of the methods introduced in this paper to the fossil data at Jacobson Lake might resolve this difference.

Although Wright presented no maps, discussion in his 1968 paper implies that the pattern from 8000 to 4000 B.P. may have resembled the circulation during the drought years of the 1930's. He referred to the climatic maps of these years presented by Borchert (1950) in which a tongue of warm, dry Pacific air extended farther east in the northern Midwest. The results of this paper indicate such a change during the mid-postglacial. According to other maps that Borchert (1950) presented, this shift in the 1930's resulted in warmer, drier conditions in Minnesota but normal conditions in New England. In this respect, his maps have been used as an analog for the period from 8000 to 4000 B.P. when Minnesota was dry but the New England pollen record showed no change toward drier conditions (Wright, 1968). On more detailed examination, the analogy does not hold because Borchert's maps (Figs. 10 and 13 in Borchert, 1950) also show a decrease in summer season precipitation and an increase in temperature in Wisconsin, but our results show no such changes (Fig. 26).

In a more recent paper, Wright (1970) has argued against the 1930's providing an adequate analogy for the climatic conditions during mid-postglacial time. Fossil data from Georgia and northern Florida (Watts, 1969, 1970) indicate that this region was dry from 10,000 to 6000 B.P. (Wright, 1970), and therefore dry part of the time the Midwest was dry. According to Borchert's maps (1950), however, the Southeast was receiving normal precipitation during the 1930's when the Midwest was dry.

The results from this paper clearly support Wright's contention (1968) that there was no synchronous xerothermic interval throughout central and eastern North America. The absence of such a period in central and northern Wisconsin makes this point clear. The exact circulation patterns that will explain dryness first in the Southeast, then in both the Southeast and Midwest, and finally in the Midwest before 5000 B.P. are yet to be found. Perhaps application of the methods developed in this paper to fossil data from the Southeast and to data from further north may provide some answers.

The only set of maps revealing atmospheric circulation patterns in the Midwest that could be used to check the results of this paper are presented by Bryson and Wendland (1967). Their maps of past air mass boundaries are based largely on reconstructions from the biota during the postglacial. They used the modern correspondence between the frontal zones of air masses and the borders of vegetation types, faunal assemblages, soil regions, and glaciers (Bryson, 1966) and translated the shifts of these boundaries into movements of air mass regions and airstream patterns.

From a general point of view, their maps agree with the results of this paper.[12] For the Midwest, the charts indicate a longer duration of northern (Pacific-north and Arctic) air masses during the late glacial than during any period of the postglacial. Unlike today's winters, northerly or northwesterly flow is shown to persist during this cold season rather than westerly flow. Their map for 8000 B.P. shows a longer duration of Pacific-south air in Minnesota than in Wisconsin, and the map for 3500 B.P. presents climatic patterns similar to the present for KM, DFB, and LM. A detailed examination of their maps indicated only one real discrepancy.

For the late glacial, they placed the southern margin of Pacific air far to the south of the glacial border in summer, and their map indicates a resultant flow of Pacific air during this season. This pattern is not consistent with the results discussed in this paper, which indicate that there were 4 months of southerly flow across KM and DFB, which probably occurred during the summer. The summer position of the southern boundary of Pacific air on their map is well south of this boundary's position as indicated in this paper.

From a consideration of the drier, somewhat warmer "Arctic" air in winter and westerly flow in summer, they also inferred that the climatic conditions in the regions of the late glacial "boreal forest" were more droughty than at present.

Wright *et al.* (1963) also arrived at similar conclusions from looking at the pollen data at KM and assigned a dry temperate climate like that of southwestern Manitoba to the late glacial period after 13,000 B.P. These conditions are not indicated by the results at KM or DFB in this paper which shows that there was more rain, snow, and cloudiness during this period and a circulation pattern that might produce these conditions.

The resolution of this difference in interpretations may have to wait until more pollen types are included in a study similar to that presented in this paper. In fact, a full understanding of the late glacial and the early postglacial climates will not be possible until such pollen types as ash, elm, and hornbeam can be included in the determination of the transfer functions. The presence of these pollen types in numbers that have no modern analog in surface pollen data have provided a real dilemma for palynologists. (Wright, 1970, provides a longer discussion of this problem; see also Davis, 1967; Cushing, 1965.) As stated earlier, including these pollen types in the pollen data produced quite improbable results for these time periods, e.g., minus 4 months of Arctic air during the early postglacial at KM. Perhaps this problem can be resolved by using a greater density of modern pollen samples in the initial analysis. Higher values of elm were found at certain sites in a set of 40 modern samples from Wisconsin alone (Webb, 1971). Elm pollen was then included in the construction of the transfer functions from this grid of Wisconsin samples. When these transfer functions were applied to the spectra from DFB, the results produced were similar to the results presented in this paper for that site. A denser network of samples from central North America might therefore allow inclusion of elm and other pollen types in the interpretation of other fossil cores.

Other work that may provide a more accurate description of the climate during the late glacial requires using a more sophisticated approach in calibrating the pollen rain. In this paper, the pollen spectra are calibrated only in terms of frequencies and durations of contemporary air masses. Changes in climate result not only from

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[12] The maps presented by Bryson and Wendland (1967) will be of assistance in the following discussion.

changes in the frequency or duration of air masses but also from changes in the characteristics of the air masses. This latter type of change is most probable at times when the source regions of air masses are changed as they were with the ice immediately to the north and with the seas colder.

A more sophisticated approach that might be used in future work would be to include among the modern climatic variables descriptions of the properties of the air masses as well as their frequencies and durations. This added degree of freedom in climatic change could then also be accounted for objectively. As a specific example, the modal temperatures (see Bryson, 1966) for the July air masses could be included along with their frequencies. Transfer functions for both sets of climatic variables could then be derived and used on the fossil pollen spectra. Time series of both the modal temperatures and the air mass frequencies would then be available for interpretation. These results might reveal that some of the pollen changes now transformed into changes in airflow patterns are better related to changes in the air mass characteristics.

CONCLUSIONS

This study represents an initial effort to apply canonical correlation analysis to the interpretation of fossil pollen data. From the discussion of previous methods of pollen interpretation, it seems clear that the logic of the quantitative interpretation scheme used in this study does not differ markedly from the logic currently justifying standard methods of pollen interpretation. This study differs only in utilizing statistical procedures to make decisions concerning the interrelations of pollen and climatic data and, thereby, takes greater advantage of the quantitative nature of pollen data. The multivariate statistical analysis of the data allows more pollen data to be incorporated effectively in the interpretive process and greater objectivity in handling these data.

From the discussion in the previous section of this paper, it should be clear that much work needs to be done in perfecting this particular line of research. More modern pollen data need to be analyzed so that new transfer functions can be calculated and applied to more cores of fossil pollen from all across North America. Maps of the derived climatic variables can then be constructed for specific times during the Holocene. Examination of these maps will then reveal the nature of past climates, and differences among these maps will reveal patterns and magnitudes of past climatic change. Such information can be used to help calibrate current climatic fluctuations.

As already suggested, more site factors and pollen-types might be included in the determination of the transfer functions. More sophisticated measures of climate might also be used, and a greater density of modern sites might be included. As a possible intermediate step, quantitative estimates of the past vegetation might be calculated in areas where the existence of quantitative measures of the modern vegetation allow the appropriate transfer functions to be determined. This reconstruction of the vegetation will aid in judging whether the changes in the pollen record result from succession under constant climatic conditions or are indicative only of fluctuations in climate. The results of this initial study will provide a valuable baseline for judging the improvements rendered by each of these changes in methodology.

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APPENDIX

Hotelling wrote the original article describing canonical correlation analysis in 1936. Recently Morrison (1967) and Glahn (1968) have given good short discussions of this same technique. The outline that follows of the mathematics involved in this form of analysis is derived mainly from these recent articles. A more rigorous mathematical discussion is given by Anderson (1958).

The following notation is used for this discussion:

n = the number of observations, sites, or levels

p = the number of variables in one set of data

q = the number of variables in the other set of data

r = min (p, q), i.e., equals the smaller of the two values p or q

X^* = $(x^*_{i,j})$, an n by p data matrix of observations of the first set of variables, where $i = 1, \ldots, n$ and $j = 1, \ldots, p$

X = $(x_{i,j})$, the matrix X^* with the variables in standardized form, i.e.,

$$x_{i,j} = (x^*_{i,j} - \bar{x}_j)/[(1/(n-1)) \sum_{i=1}^{n} (x^*_{i,j} - \bar{x}_j)^2]^{1/2} \qquad \text{(A.1)}$$

Y^* = $(y^*_{i,j})$, an n by q data matrix of observations of the second set of variables

Y = $(y_{i,j})$, the matrix Y^* with the variables in standardized form

F = n by $p + q$ data matrix of variables in standardized form

= $[X : Y]$

A = p by r matrix of canonical functions for the first set of variables X

= (a_i) where a_i is a canonical function and one of r (p by 1) column vectors; $i = 1, \ldots, r$

B = q by r matrix of canonical functions for the second set of variables Y
= (b_i) where b_i is a canonical function and one of r (p by 1) column vectors; $i = 1, \ldots, r$

U = r by n matrix of canonical variates (this terminology from Anderson, 1958)
= (u_i) where u_i is a canonical variate and one of r (1 by n) row vectors; $i = 1, \ldots, r$
= ${}_rA'_pX'_n$

V = r by n matrix of canonical variates
= (v_i) where v_i is a canonical variate and one of r (1 by n) row vectors; $i = 1, \ldots, r$
= ${}_rB'_qY'_n$

Λ = r by r diagonal matrix of canonical correlation coefficients

$$= \begin{bmatrix} \lambda_1 & & & & & \\ & \cdot & & & 0 & \\ & & \cdot & & & \\ & & & \lambda_i & & \\ & 0 & & & \cdot & \\ & & & & & \lambda_r \end{bmatrix}.$$

The problem of canonical correlation analysis is finding the linear compounds

$$\begin{aligned} {}_1u_{i_n} &= {}_1a'_{i_p}X'_n \\ {}_1v_{i_n} &= {}_1b'_{i_q}Y'_n \end{aligned} \qquad \text{(A.2)}$$

such that the correlation of u_1 and v_1 is greatest, the correlation of u_2 and v_2 is greatest among all linear compounds uncorrelated with u_1 and v_1, and so on for all r possible pairs (Morrison, 1967, p. 214). The canonical correlation coefficient is a measure of how well the spatial array of u_i's coincides with that of v_i's.

Solving for the above sets of u's and v's under the constraints of orthogonality as given in the following equations[1] (Glahn, 1968):

$$\begin{aligned} {}_rA'_pX'_nY_qB_r &= n\,{}_r\Lambda_r \\ {}_rA'_pX'_nX_pA_r &= n\,{}_rI_r \\ {}_rB'_qY'_nY_qB_r &= n\,{}_rI_r \end{aligned} \qquad \text{(A.3)}$$

leads one to the following homogeneous linear equations:

$$\begin{aligned} (R_{11}^{-1}R_{12}R_{22}^{-1}R_{21} - \lambda_i^2 I)A_i &= 0 \\ (R_{22}^{-1}R_{21}R_{11}^{-1}R_{12} - \lambda_i^2 I)B_i &= 0 \end{aligned} \qquad \text{(A.4)}$$

in which the R's are components of the partitioned correlation matrix

$${}_{p+q}R_{p+q} = \begin{bmatrix} R_{11} & : & R_{12} \\ \cdots & & \cdots \\ R_{21} & : & R_{22} \end{bmatrix}$$

derived from the partitioned data matrix ${}_nF_{p+q} = [X : Y]$ of normalized variates. Solution of the determinantal equations:

$$\begin{aligned} |R_{11}^{-1}R_{12}R_{22}^{-1}R_{21} - \lambda_i^2 I| &= 0 \\ |R_{22}^{-1}R_{21}R_{11}^{-1}R_{12} - \lambda_i^2 I| &= 0 \end{aligned} \qquad \text{(A.5)}$$

then provides the values of λ_i, a_i, b_i, u_i, and v_i.

In order to set up a series of equations that permit translation of pollen data into climatic information by way of the canonical functions and correlations, an equation of the following form

$${}_n\overset{\Lambda}{Y}_q = {}_nX_pA_r\Lambda_rB_q^{-1} \qquad \text{(A.6)}$$

is used (Glahn, 1968). This equation also represents a least squares solution for Y and is identical in form to the multiple regression equation which is written as ${}_n\overset{\Lambda}{Y}_q = {}_nX_p\overset{\Lambda}{\beta}_q$ where in the case of canonical correlation ${}_p\overset{\Lambda}{\beta}_q = {}_pA_r\Lambda_rB_q^{-1}$.

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[1] These equations show explicitly that the canonical variates are mutually orthogonal, i.e.,

$$\begin{aligned} u_iv_j' &= 0 \text{ if } i \neq j \\ u_iu_j' &= 0 \text{ if } i \neq j \\ v_iv_j' &= 0 \text{ if } i \neq j \end{aligned}$$

According to Glahn (1968), those canonical patterns of little significance may be excluded from this solution by setting their respective canonical correlations equal to 0. Therefore,

$$ {}_n\hat{Y}_q = {}_nX_pA_s\Lambda_sB_q^{-1} \qquad (A.7) $$

where $$\Lambda = \begin{bmatrix} \lambda_1 & & & & & \\ & \ddots & & & 0 & \\ & & \lambda_s & & & \\ & & & 0 & & \\ & 0 & & & \ddots & \\ & & & & & 0 \end{bmatrix}$$ and $s<r$.

and $$ {}_p\hat{\beta}^*_q = {}_pA_s\Lambda_sB_q^{-1} $$
is a matrix of canonical regression coefficients.

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