Tentative Climatic Patterns for some Late Glacial and Post-Glacial Episodes in Central North America

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TECHNICAL REPORT NO. 34

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The University of Wisconsin
Department of Meteorology
Madison, Wisconsin 53706

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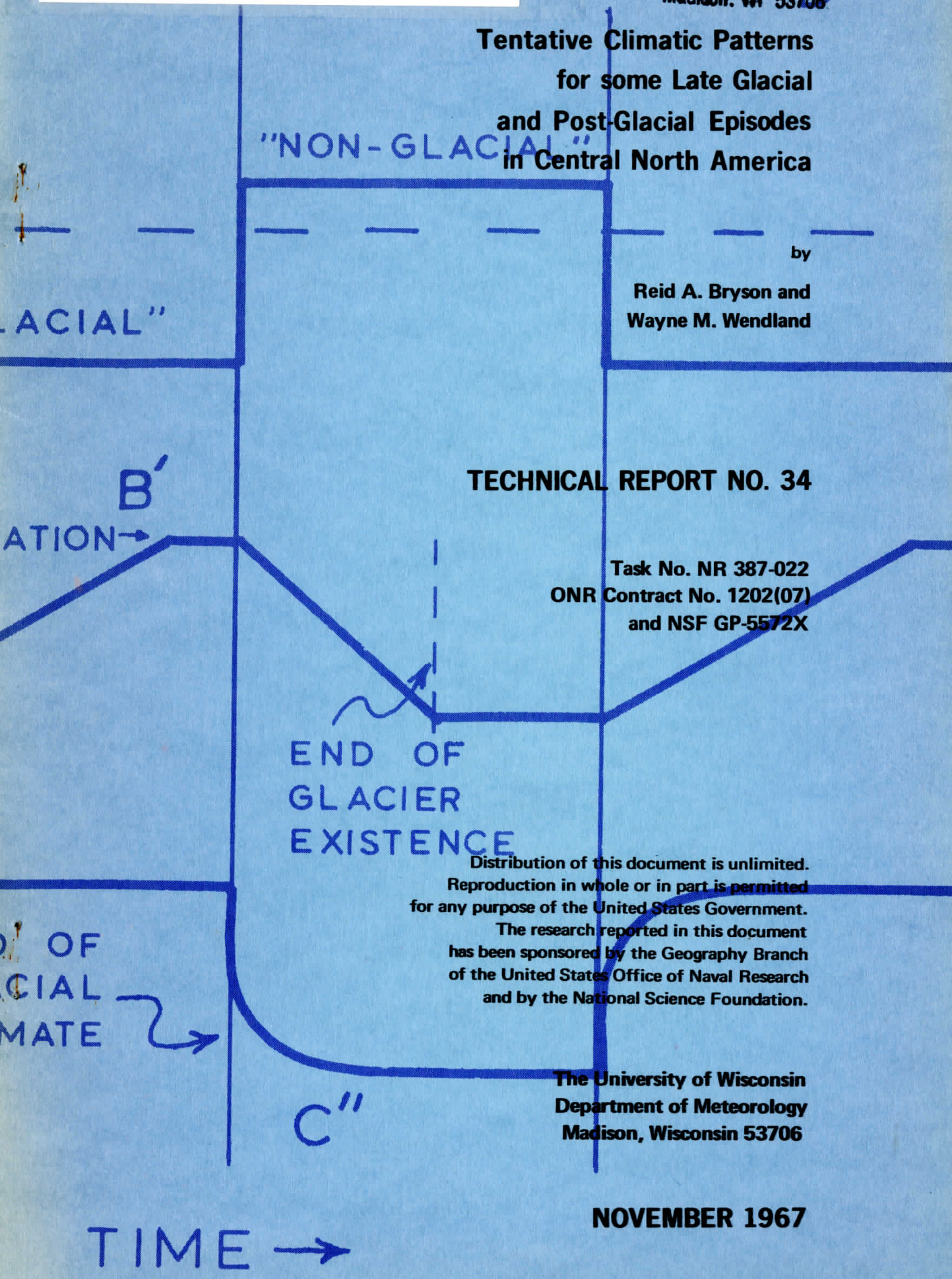

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The Modern Climatic Pattern

Before one attempts a reconstruction of past climates, it would appear necessary to have an appropriate knowledge of present climates. It is unlikely that there would be serious dissent to this statement among climatologists -- but in the context of the present discussion the key word of the statement is "appropriate". Clearly, we do have an adequate outline of the distribution of temperature, precipitation, wind, humidity, etc. for the present climate of North America, but is this the appropriate set of climatic fields for interpretation of the past with the current state of paleoclimatic knowledge? Evidences of past climate do not appear as readings of a thermometer, a rain-gauge, or a wind vane, but rather as natural phenomena which represent, usually, complexes of climatic parameters acting on soils, topography, or biota -- generally in rather vaguely understood combinations -- and often only in the sense of present or not present rather than as graded values that could be mapped with isopleths.

It would appear that an appropriate paradigm would be a description of the present distribution of climatic complexes, by naturally occuring categories, which were in turn meaningful in terms of the types of paleoclimatic evidences which are available. Here we must be careful to avoid circular reasoning. For example, the Köppen climatic classification scheme essentially starts with biotic distributions, for which arbitrarily selected climatic parameters are sought which best fit the boundaries of the biotic regions. Generally these are simple parameters, implying that single variables are limiting factors along the boundaries of the biotic regions. We have no *a priori* reason to assume this is true. These perhaps fortuitous parallelisms of, say, isotherms and biotic boundaries are then the basis for climatic regionalizations everywhere, ignoring the interactions of climatic parameters which might reasonably determine the suitability of the climatic environment for a particular biotic type. Use of such a system for a paleoclimatic reconstruction assumes that the same value of the same parameter that appears limiting today was also limiting in the past. The biotically defined climate is then used to describe the climate of the biotic region. It would seem philosophically more satisfying if one could identify natural climatic complexes which array themselves in natural climatic regions with distinct boundaries not arbitrarily chosen by the investigator, and which are congruent with the biotic regions and their boundaries. This might be regarded as wishful thinking if it were not for the probability that biotic communities evolved in adjustment to (or towards adjustment to) the climatic complexes present in their region and extended as far as this complex extended without the whole being absolutely limiting.

Naturally occuring atmospheric complexes with distinct boundaries have been recognized for many decades and are generally subsumed under the concepts of *airmass* and *front*. It has recently been shown (Bryson 1966) that it is possible to delineate regions bounded by the modal positions of distinct inter-airmass boundaries (fronts) and occupied by a definite mean annual sequence of airmasses (Figs. 66 and 67).

As Figs. 68 and 69 indicate, these meterorologically defined regions coincide quite well with certain major biotic regions of about the same degree of generalization as the climatic regions. Within the climatic regions there are mesoclimates and microclimates of scale comparable to the finer divisions of the biota. (For purposes of climatic reconstruction, using biotic evidence, it would be fruitful to identify the particular combinations of plant or animal species that best fit the independently defined climatic regions, rather than trying to find climatic regions that fit the independently defined biotic regions. Similarly, the identification of climatically significant combinations of pollen taxa would make pollen profiles easier to use for paleoclimatic purposes.)

It is on the basis of this correspondence between the independently derived climatic and biotic charts that the ideas of this paper will be developed. It is assumed that the characteristic airmass combination as it varies during the year at a given place represents the significant climatic complex operating as an ecological control on the biotic community of that place.

Certain other considerations are involved in the following paragraphs and several assumptions will be made. Most will be identified as they appear, but it would seem appropriate to discuss some of the major ones explicitly here. We will assume that climate is the ultimate ecological control (Hare 1953). It is pointless to argue the question of macroclimate versus microclimate in relation to substrate at the scale of our present considerations. After all, the macroclimate determines the modal microclimate, and we are concerned at the present with "climata" and biota which are regionally dominant. (The term *climata* is coined here as an appropriate parallel to the term *biota*. We define it to mean the naturally occurring complexes of meteorological parameters found in the various climatic regions, much as the various biota occupy biotic regions.) These clearly cut across geological substrate distributions. Soils, on the other hand, depend on parent material, plant cover, and climate and hence are not independent parameters.

A second assumption is that glaciers retreat in a "post-glacial" climate. This seems obvious but is often not recognized in the paleoclimatic literature. A corollary is that the time of retreat from a terminal moraine marks the end of the "glacial" climate -- the presence of an extensive ice sheet does not indicate the presence

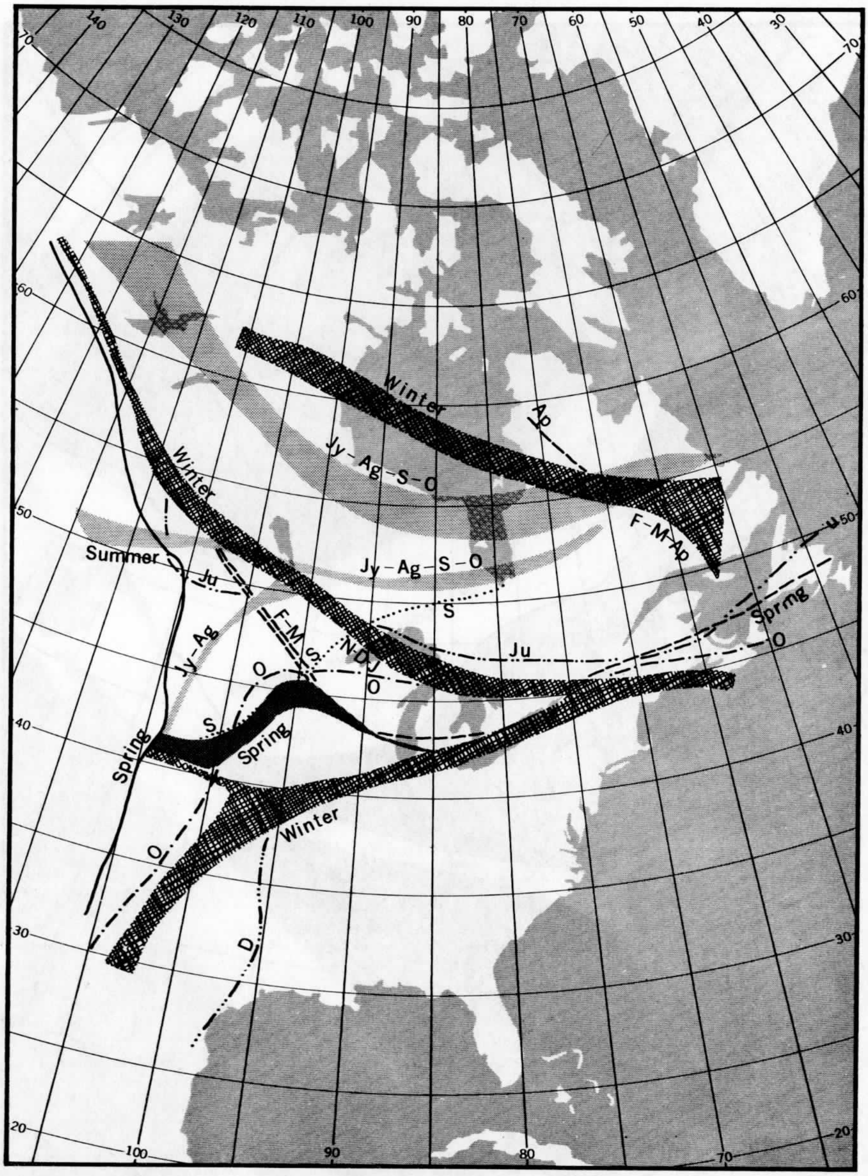

Figure 66. Composite chart showing the seasonal positions of mean confluences between major airstreams, as determined from the monthly surface resultant streamline charts. The hatched bands give the total range of the monthly mean position of the major confluences during the seasons indicated. (Bryson 1966)

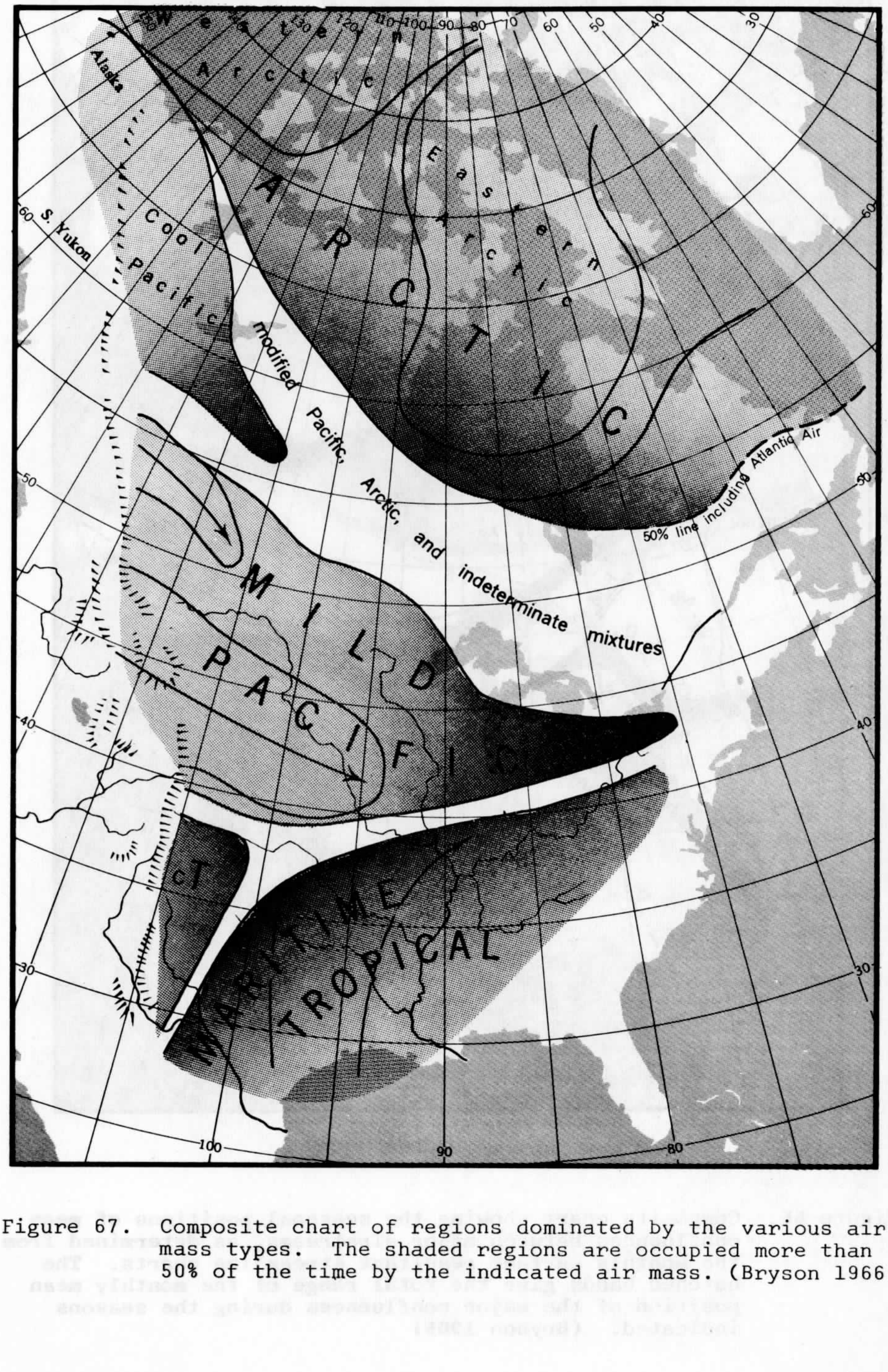

Figure 67. Composite chart of regions dominated by the various air mass types. The shaded regions are occupied more than 50% of the time by the indicated air mass. (Bryson 1966)

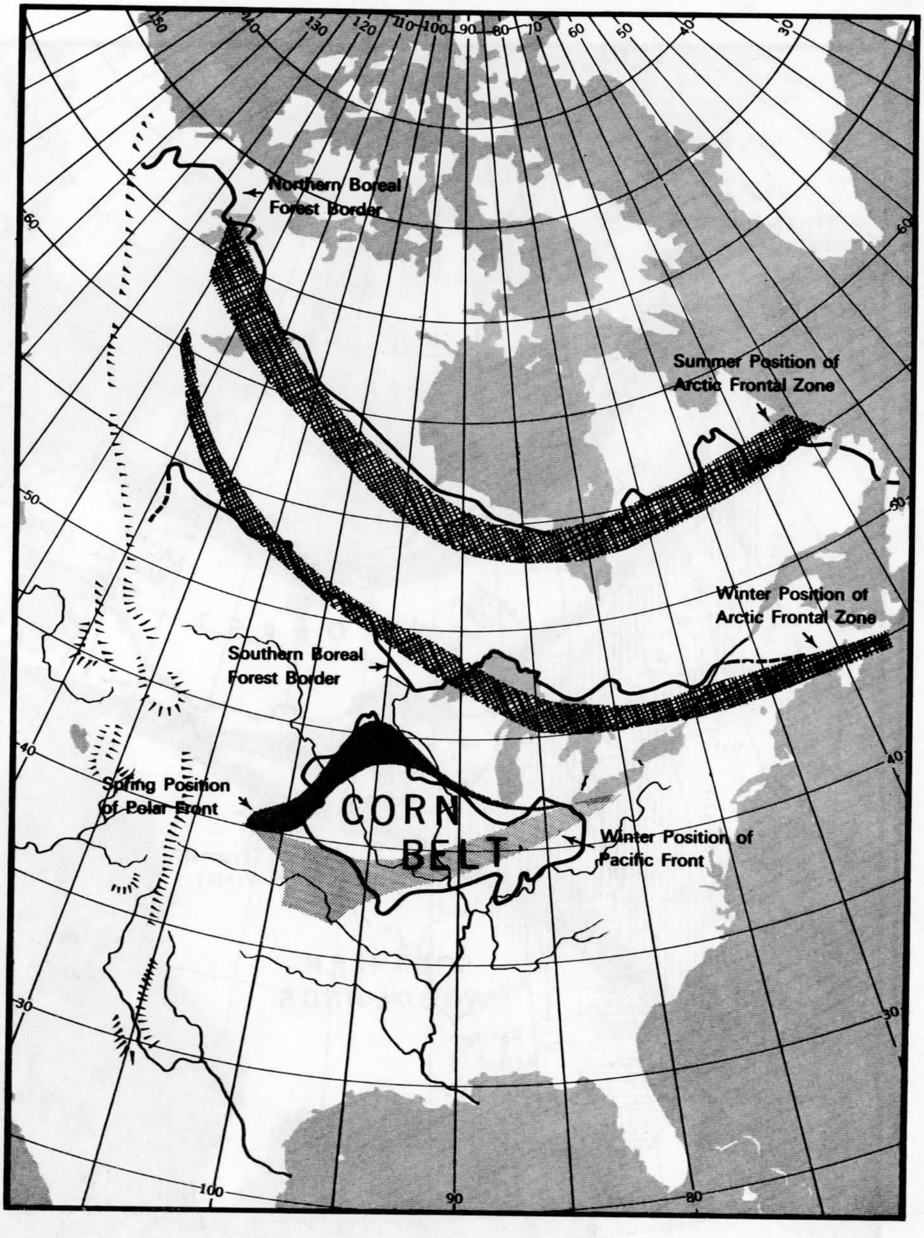

Figure 68. The coincidence of the "corn belt" and "boreal forest" biotic regions with meteorologically defined climatic (air mass) regions. Climatic regions are taken from Bryson (1966), Fig. 32: "corn belt" from "soils of the North Central Region of the United States" (1960): and the boreal forest generalized somewhat from Rowe (1959) and Larsen (1967).

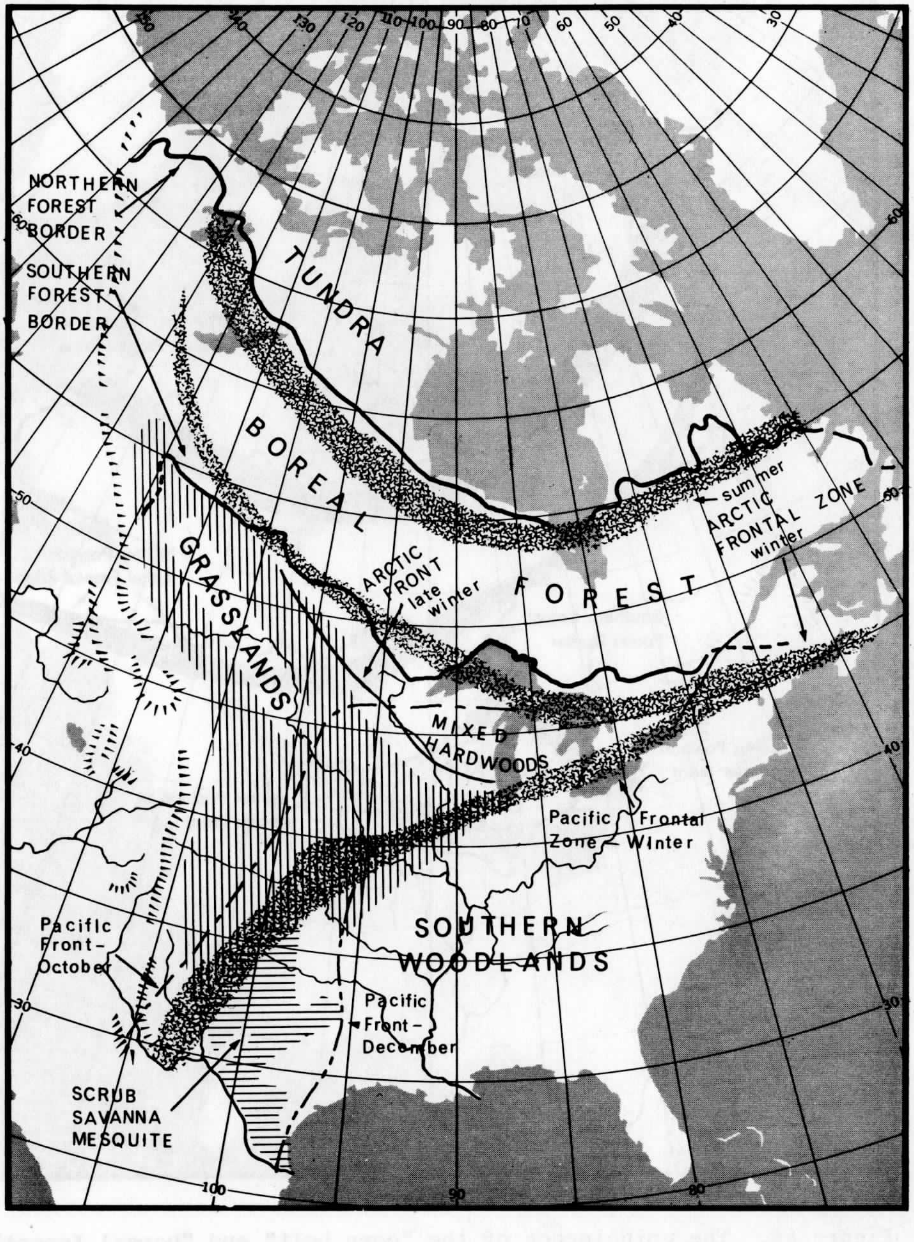

Figure 69. The coincidence of biotic regions with meteorologically defined climatic regions. Climatic regions taken from Bryson (1966), Fig. 32: "grasslands" and "scrub savanna-mesquite" from Küchler (1964).

of a "glacial" climate. The rationale of this statement is easily seen by use of an electrical analogy. If we think, for a moment, of the sequence of climates as a square wave, an alteration of "glacial" and "non-glacial" climates with abrupt changes from one to the other, we can think of the accumulation of snow in glaciers as the integral of this square wave (Fig. 70), which is a triangular or "saw-tooth" wave unless limiting or "clipping" occurs. Qualitatively the sequence shown in Fig. 70 is as follows:

(1) During a "non-glacial" climate, (A), no glaciers accumulate.

(2) When the climate changes to "glacial" (B), ice starts to accumulate and continues to do so as long as the climate remains glacial unless the accumulation spreads to low enough altitudes or latitudes for wastage to equal supply, in which case the total glacial mass remains constant and the saw-tooth is "clipped" (B' in the diagram).

(3) When the "glacial" climate ends, the glacial mass starts to decline, and this retreat may extend well into the succeeding "non-glacial" climate (C). It should be noted that the glacial maximum is at or near the end of the "glacial" climate.

(4) The phase shifts of the climatic indicators (glaciers, sea level, vegetation, etc.) depend on their time-constants. Thus vegetation may show the presence of a "glacial" climate before the glaciers have grown to significant magnitude (B") and "post-glacial" characteristics before significant glacial retreat has occured (C").

(5) Even though there is evidence that climate does act somewhat like a square wave, i.e. with rather sudden shifts at the ends of successive climatic episodes, the general conclusions listed above would be equally applicable to a continuously varying climate.

A third assumption is that within the past ten or fifteen millenia a mix of airmasses occuring in the same frequency and annual sequence as at the present would be associated with a similar biotic system to that with which it is now associated. Similarly, significant differences in airmass frequency or characteristics should produce somewhat different biota, e.g. the boreal forest in Valders time might have a different floristic composition if the airmass characteristics in Valders time were different, even if the general airmass frequencies and sequence were similar to the present. This is equivalent to the geological concept of uniformitarianism, namely, that the present is the key to the past. A corollary of this assumption is that past climates differed from present climates in quantity, but not in kind.

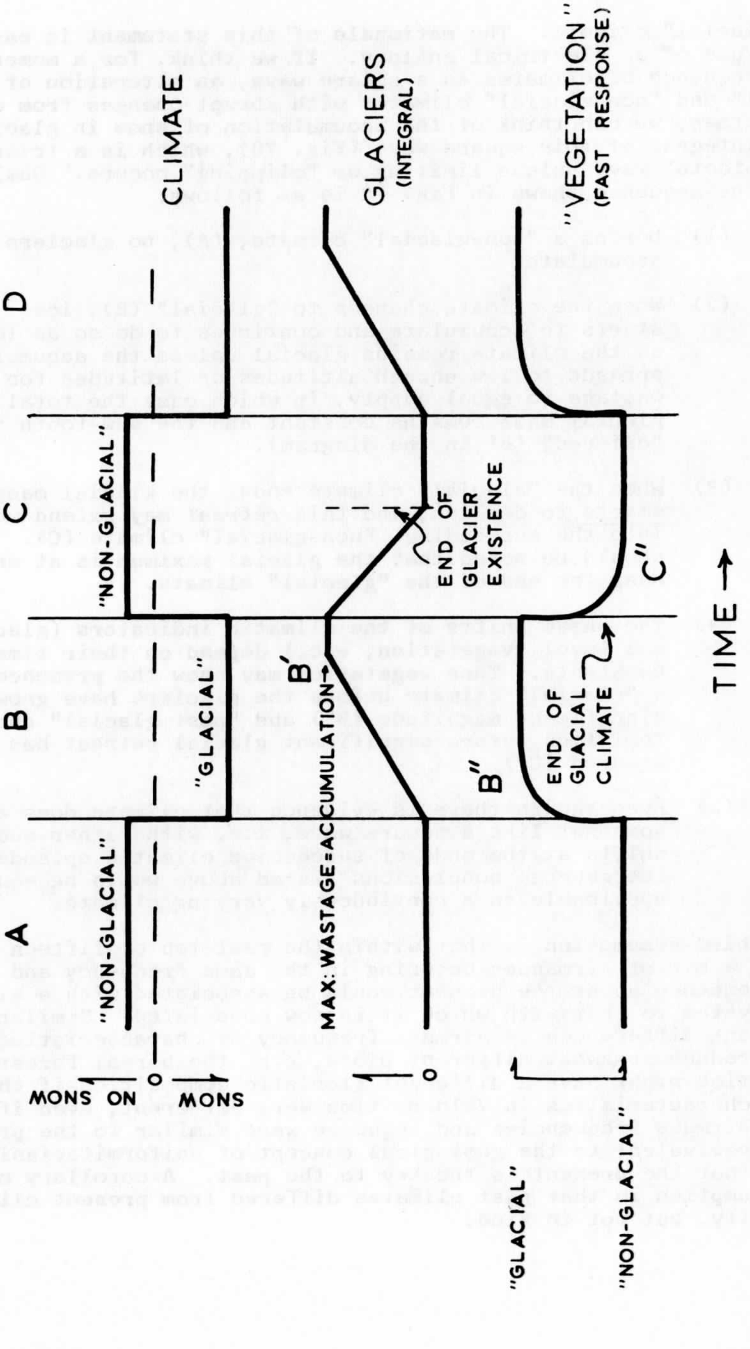

Figure 70. Suggested glacial and vegetative response to abrupt temperature changes with time.

Choosing the Episodes

The purpose of this paper is to present a few tentative reconstructions of past airmass regimes. Until more data are brought together in appropriate format and with good time control, these reconstructions will be necessarily rough and subject to improvement. Thus we have chosen to attempt partial reconstructions for three times: the late glacial period of about 13,000-10,000 years ago, the period around 9,000-8,000 years ago, and the period around 5,000-3,500 years ago plus some comments on the smaller fluctuations since that time. It appears that in the past five millenia the pattern has been sufficiently close to the present that climatic variations might best be discussed in terms of perturbations from the present.

The rationale for choosing these particular intervals is primarily that they are convenient and represent distinctly varied patterns. Secondarily they fit the world-wide sequence of climatic episodes. In principle, the climatologist knows that the atmosphere acts as a unit and that a major change in Europe cannot occur without a concurrent, though usually different, change in North America. Meteorological research papers too numerous to reference have established the hemispheric integrity of the atmosphere, and there is no reason to believe that the mechanics of the atmosphere were different in the past. Indeed, an analysis of radiocarbon dates and bog stratigraphy indicates that the dates applicable to the Blytt-Sernander European sequence are equally applicable in North America, though the relative effect of climatic changes in the two continents was different (Nichols 1967). For example, the end of the Atlantic period (*ca.*3,000 B.C.) appears more important in Europe than the end of the Early Sub-boreal (*ca.*1,500 B.C.) but the latter appears to have been more important in central Canada. There appears to be good reason for adopting the European terminology for North America as well (Baerreis and Bryson 1965; Bryson 1965) and this convention will be used in the remainder of this paper as far as possible.

With the limited precision possible, we may combine Mankato, Two Creeks, and Valders times and refer to them all as Late Glacial, for it is clear that these were more like each other than any one was like the pattern which followed the Late Glacial. Most of the pollen diagrams which reach back into the Lake Glacial show an abrupt and distinctive change into the postglacial. Evidently a rapid glacial retreat (in a postglacial climate) followed, but the Cochrane moraines of around 8,000 years ago (Falconer *et al.* 1965) indicate that a minor glacial episode intervened which terminated at about that time. This would appear to correspond to the Piori oscillation and our climatic reconstruction might then refer to Boreal time.

The third chart will be drawn for Early Sub-boreal time, 3,000-1,500 B.C., but it would appear that the chart for Atlantic time would not be much different on the warm side or the Sub-Atlantic on the cold side. Indeed though we will discuss the minor climatic changes of the past 2500 years, it is clear that we can differentiate these minor episodes because of a wealth of data rather than because they are as distinctive as the earlier episodes. The following table lists the more recent climatic episodes, as we recognize them at the University of Wisconsin Center for Climatic Research, though many authorities might class the later ones as minor details of the Sub-Atlantic.

TABLE 23

CLIMATIC EPISODES IN THE LAST 2500 YEARS

Episode	Rough Date
Recent	1850 - 1960 A.D.
Neo-boreal	1550 - 1850 A.D.
Pacific II	1450 - 1550 A.D.
Pacific I	1200 - 1450 A.D.
Neo-Atlantic	900 - 1200 A.D.
Scandic	400 - 900 A.D.
Sub-Atlantic	550 B.C. - 400 A.D.

(several sub-episodes identifiable)

It should be borne in mind that the shorter sub-divisions that may be recognized in the last few millenia may be too short for even the faster responding climatic indicators to reach full equilibrium with the climate though it is clear that locally significant changes did occur. Thus the vegetation should have a general Sub-Atlantic character through the last two millenia, but the concept of full climax must be used with caution and changes sought primarily in minor aspects of the floristic communities except in the vicinity of sharp ecotones. An examination of the literature suggests that the stability of the core of a biotic region compared to the instability of its borders in response to minor climatic oscillations is not widely recognized. (If we regard climate as limiting the biota, and also adopt the principle that climatic variation is primarily expressed as small displacements of the fields of climatic parameters -- the small perturbation approach -- then the impacts of that variation will be primarily at the boundaries of the biotic regions. In other words, ecotones are sensitive to climatic change and the heart of the biotic region is far less so.)

The Late Glacial Climatic Pattern

The accumulation of faunal remains in the New Paris sinkhole in western Pennsylvania may be divided into two layers: an upper stratum representing species presently living in the northeastern United States and particularly Pennsylvania, and a lower stratum of Late Glacial remains representing species currently living mostly in the boreal forest (Guilday *et al.* 1964). The maximum number of Late Glacial species from the lower stratum are presently found along an east-west axis just south of James Bay (Fig. 71) along what is presently the southern edge of the lichen woodland and the northern edge of tropical airmasses in summer (Fig. 66). Using our assumption that the present is the key to the past, this would suggest that the corresponding biotic and climatic boundary in Late Glacial time lay across central Pennsylvania.

The Late Glacial "Jones Fauna" of southwestern Kansas (Hibbard and Taylor 1960) is mostly found at the present time in the steppe area of the Dakotas and Montana (Fig. 72). This is just south of the boreal forest, i.e., in the region occupied by Pacific air in fall and winter, Arctic air in spring, and by Pacific air with incursions of Tropical air in summer. It is assumed that this sequence was characteristic of southwestern Kansas in Late Glacial time. If so, then Nebraska should have been in the boreal forest, and the pollen evidence indicates that it was (Wright 1964).

Since the frontal boundaries which delineate the airmass and airstream regions are anchored to the major breaks in the Cordillera as shown by Bryson (1966), and since the physics of climate requires that mean frontal boundaries follow broad, sweeping patterns, the information above is adequate to allow us to rough in the modal positions of certain climatic boundaries such as the southern edge

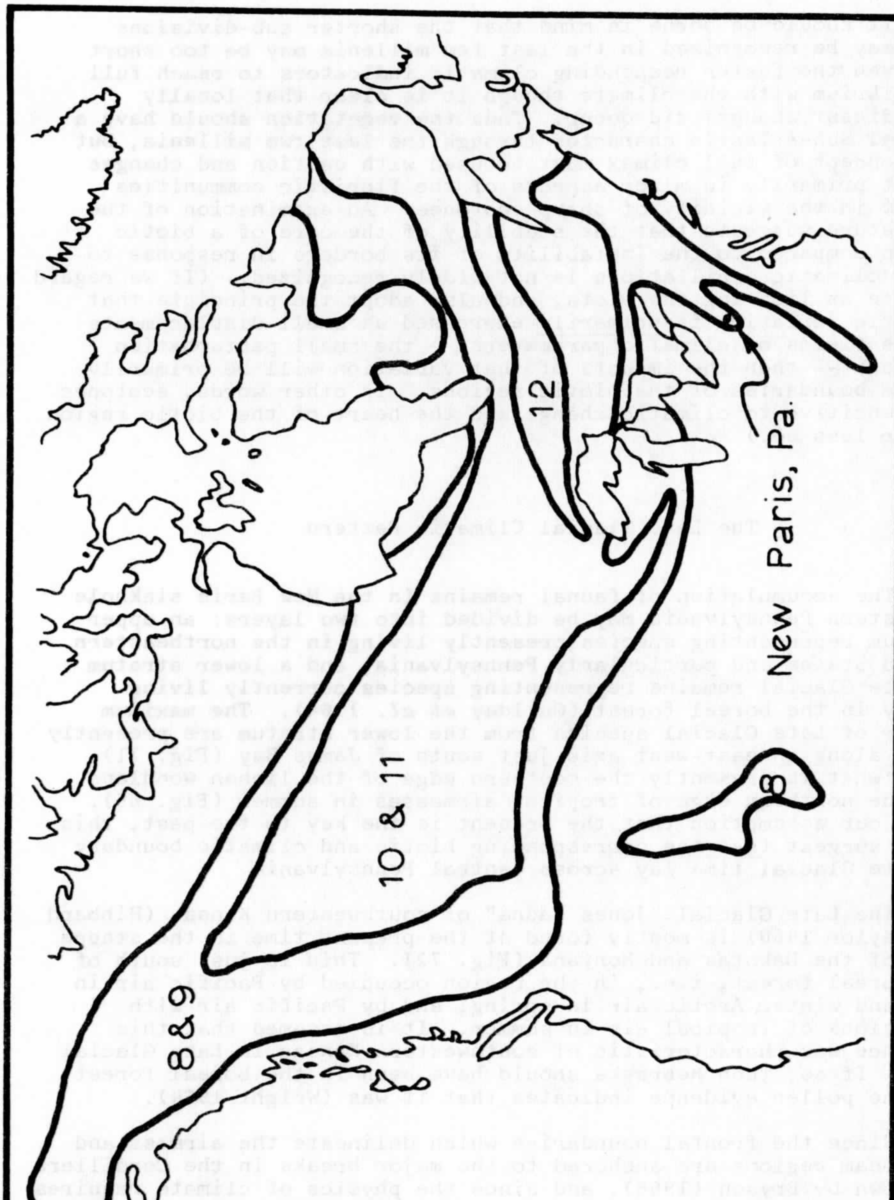

Figure 71. Present range overlap of the species of mammals found below 6 meters in the New Paris No. 4 site. Numbers within the areas indicate the number of species whose ranges overlap within the indicated area at the present time. (after Guilday *et al.* 1964).

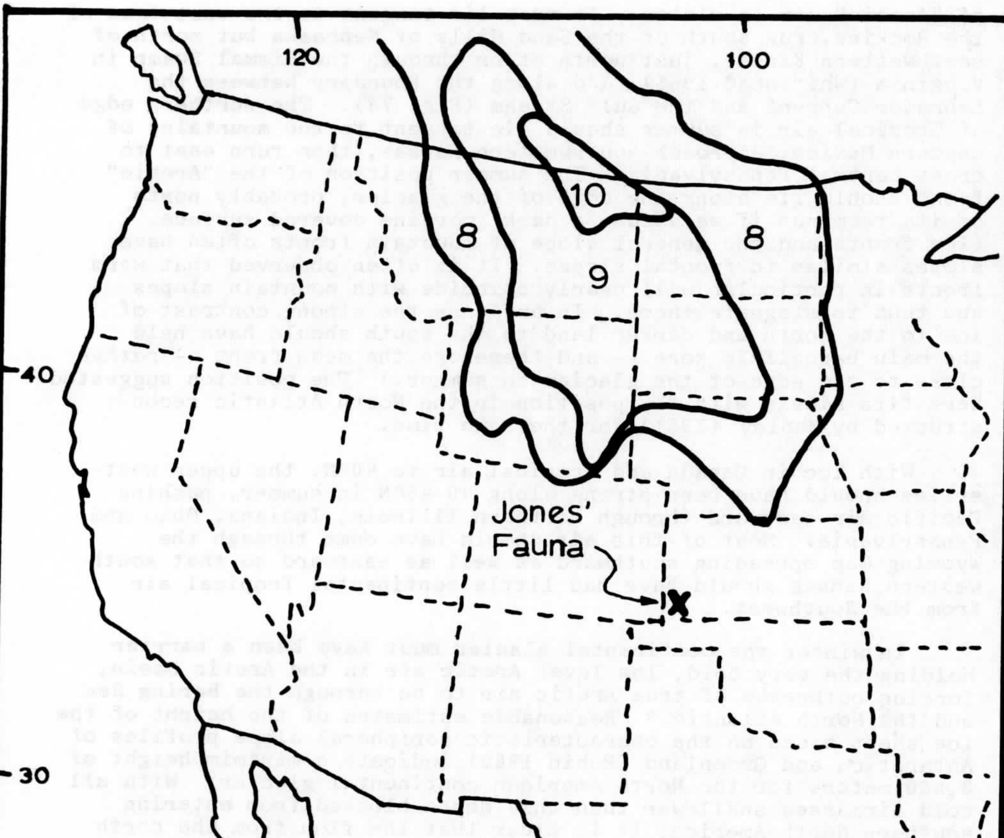

Figure 72. Present range overlap of the nine species of mammals and one amphibian of the Jones' fossil fauna. Numbers indicate the number of species whose ranges overlap within the indicated area at the present time. After Hibbard and Taylor (1960).

of "Arctic" air in winter. It must lie tangent to the east face of the Rockies, run south of the Sand Hills of Nebraska but north of southwestern Kansas, just north of or through the Dismal Swamp in Virginia (Whitehead 1965), and along the boundary between the Labrador Current and the Gulf Stream (Fig. 73). The northern edge of Tropical air in summer should lie tangent to the mountains of eastern Mexico, approach southwestern Kansas, then turn east to cross central Pennsylvania. The summer position of the "Arctic" front should lie along the edge of the glacier, probably north of its terminus if we assume a dark, moraine covered surface. (Ice fronts and the general slope of mountain fronts often have slopes similar to frontal slopes. It is often observed that warm fronts in particular will nearly coincide with mountain slopes and tend to stagnate there. In any case the strong contrast of ice to the north and darker land to the south should have held the main baroclinic zone -- and therefore the mean front -- rather close to the edge of the glacier in summer.) The position suggested here fits nicely with the position in the North Atlantic reconstructed by Manley (1951) for the same time.

With ice in Canada and Tropical air to 40°N. the upper westerlies should have been strong along 40-45°N in summer, pushing Pacific air eastward through northern Illinois, Indiana, Ohio and Pennsylvania. Most of this air should have come through the Wyoming Gap spreading southward as well as eastward so that southwestern Kansas should have had little continental Tropical air from the Southwest.

In winter the continental glacier must have been a barrier holding the very cold, low level Arctic air in the Arctic Basin, forcing outbreaks of true Arctic air to be through the Bering Sea and the North Atlantic.* Reasonable estimates of the height of the ice sheet based on the characteristic peripheral slope profiles of Antarctica and Greenland (Robin 1962) indicate a minimim height of 3,500 meters for the North American continental glacier. With all cold airmasses shallower than this depth blocked from entering southern North America, it is clear that the flow from the north into the midwestern United States would have been Katabatic, with adiabatic heating on the order of 30-35° Centigrade. Any reasonable assumption of representative temperatures on the ice-cap averaging higher than -60° Centigrade would mean air entering the United States no colder than at present and usually warmer (The Late Glacial ice cap was about the size and height of Antarctica. South Pole temperatures in winter are about -60° Centigrade and Antarctic coastal stations about -17° Centigrade which is about the same as present day northern North Dakota in January. Remembering that the North American ice cap was at much lower latitude than Antarctica, with shorter winters and more radiation, temperatures outside the glacial terminus must have been somewhat warmer than Antarctic coastal stations today.)

*It is inconceivable in this circumstance that the Arctic Ocean should have been ice-free or even partially open.

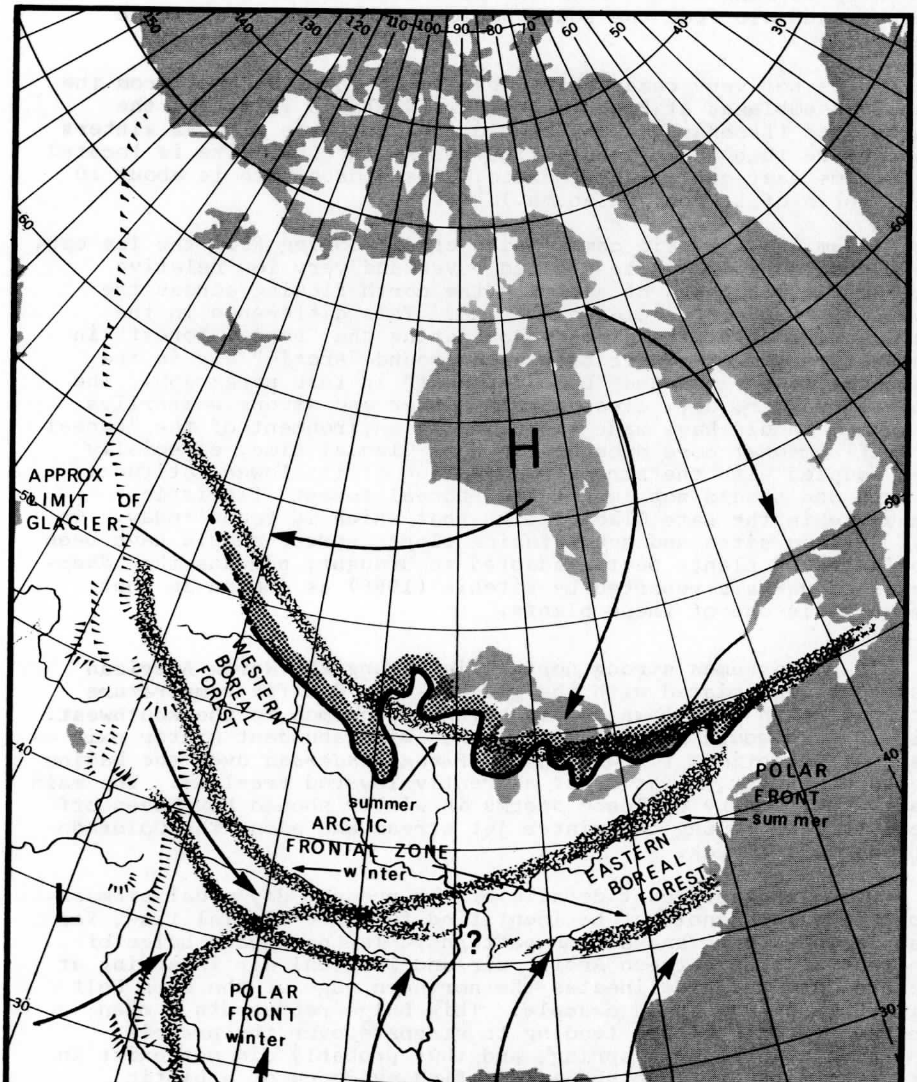

Figure 73. Partially reconstructed map of mean frontal zones during late glacial time (13,000 to 10,000 years ago). Southern glacial limit as shown is a summary of information found in Wright and Frey (1965).

Adiabatic warming of air from the west would be as great as at present, and air from the south would be about as warm as the present.

It is not very remarkable, therefore, that evidence from the faunal assemblages at Blackwater Draw (Sellards 1952) and the Domebo site (Leonhardy 1966) should indicate Late Glacial winters less severe than the present. (The Blackwater Draw Site is located in extreme east-central New Mexico. The Domebo Site is about 10 miles north of Lawton, Oklahoma.)

Assuming adiabatic compression of air coming from the ice cap, there should have been less cloud cover and very low relative humidity in outbreaks of air from the north flowing across the "boreal forest" of Late Glacial time. This difference in the characteristics of the airmass dominating the "boreal forest" in winter is why quotes have been used around "Arctic" air in the preceding paragraphs and "boreal forest" in this paragraph. The somewhat warmer, dry, clear air in winter and strong westerlies in summer should have made the climatic environment of the "boreal forest" somewhat more droughty in Late Glacial time, especially when coupled with the stronger radiation of its lower latitude. In turn one should not look for a "boreal forest" floristic community in the Late Glacial like that which is found today. On well drained sites and south-facing slopes spruce should have been supplanted by plants better adapted to drought; perhaps the *Shepherdia canadensis* reported by Ritchie (1966) as common in that community is one of these plants.

If one assumes strong northerlies along the North American west coast associated with the glacier-open Pacific temperature contrast, then deep lows should have been common in the southwest. This in turn would mean cloudy weather with abundant winter rain -- a situation optimum for widespread *Pinus ponderosa* over the basins of the southwest, or at least a greatly lowered treeline. The main tracks followed by cyclonic storms in winter should have been off the Gulf Coast along the winter jet stream and along the Colorado-Cape Hatteras track.

Certain significant details of the present day modal airmass-front pattern cannot yet be identified for Late Glacial time, for example the spring and autumn patterns. The northward bulge of the frontal zone between Arctic air and Tropical air in spring at the present, which delineates the northern edge of the corn belt (Figs 66 and 68), is an example. This bulge represents a mean warm sector of cyclones tending to stagnate over the prairie provinces of Canada in spring, and thus probably did not exist in Late Glacial time. One should not find evidence of a biotic community exactly equivalent to the tall-grass prairie in the Late Glacial, therefore.

Extending the Bjerknes circulation theorum to the case of an internal rather than an external boundary one finds that if the mean vorticity in a region is cyclonic, the circulation about a solid mass protruding up through the level being considered should be anti-cyclonic. Thus the circulation near the top of the ice cap should have been anticyclonic since the general vorticity must have been cyclonic. That this should be a cold-core anticyclone is indicated by the cold temperatures near the surface of the ice cap. A reasonable winter mean upper air flow pattern would indicate: (1) a cold-core anticyclone near the surface of the glacier, (2) reversal to a trough of low pressure above the surface anticyclone, (3) northerlies along the west coast, (4) a trough in the southwest United States, (5) cold outflow through the Bering Sea and North Atlantic and (6) the main jet stream over the Gulf Coast or northern Gulf. These features would imply frequent deepening of cyclones off Newfoundland which would provide an influx of moisture to maintain the glacier.

The Boreal Pattern

One of the striking features of pollen diagrams from central North America is the abrupt transition from Late Glacial to post-Glacial pollen assemblages (e.g., McAndrews 1966; Ritchie 1964; West 1961 and many others). Since the vegetation has a shorter time constant than a continental glacier, this is *prima facie* evidence for a quasi-square wave behavior of the climate, as suggested above, but the main significance to our present discussion is in the indication of an abrupt change in circulation pattern. Where adequately dated, the sudden collapse of the Late Glacial pattern of boreal forest appears to have occurred about 10,500 years ago to be replaced as far northward as southwestern Manitoba by grassland, and in northeastern Minnesota and Wisconsin by a jack pine-red pine forest similar to that of 400 years ago. (This is not meant to imply that the "jackpine" community of Boreal time in northwestern Minnesota was the same as in the later period. As pointed out by numerous authors, including McAndrews, we must bear in mind the effect of greater soils development as postglacial time progresses. This is one of several reasons why biotic details might be different even in two identical climatic episodes.)

This implies that a rapid change from boreal forest to grassland occurred over vast areas of the northern plains, an ecological event that could not have been without significant impact on the big game hunters of the plains and their cultures. The jack pine-red pine assemblage in turn disappeared rather abruptly about 8,500 years ago to be replaced by grassland (McAndrews 1966) in Minnesota or oak savanna characteristic of the forest-prairie ecotone in eastern Wisconsin (West 1961).

Around 8,000 years ago there was still a large amount of continental ice in the Cochrane ice sheet, but it must have been much thinner than during Valders time, producing less mountain effect on the circulation of the atmosphere. Some Arctic air must have flowed south between the Cordillera and the ice sheet in winter, and the main meridional temperature contrast in summer must have been at about latitude 50-55°N in mid-America. Strong westerlies must have prevailed across North America in mid-latitudes, extending the grassland climate of dry, subsident Pacific air far

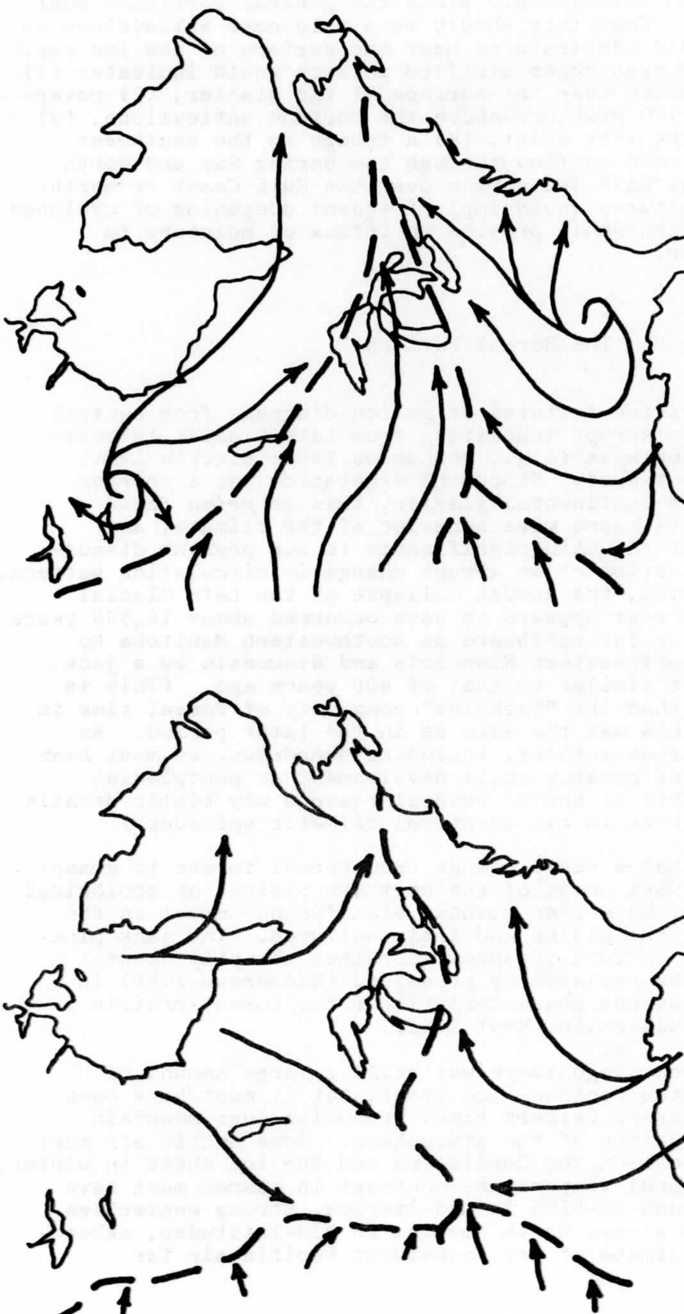

Figure 74. Schematic drawing showing the eastward penetration of Pacific air during times of low zonal index (left), and high zonal index (right).

eastward, almost to the edge of the ice in Manitoba -- in other words somewhat farther east than at the present time. Under these circumstances there should have been fewer deep lows over the southwest and a much drier climate.

Some outlines of the climatic pattern during the Boreal can thus be reconstructed by modifying the present day pattern to reflect the winter position of the jet stream near the Gulf coast, the summer position five to seven degrees farther south than now, and with generally stronger westerlies across the northern United States. The effect of stronger westerlies is shown schematically in Fig. 74, and the reconstruction of those portions of the tentative Boreal climate pattern which seem reasonable at present are given in Fig. 75.

The significant feature of the climatic-biotic pattern for Boreal time was the far northeast displacement of the forest-grassland ecotone while the ice still existed far south into Manitoba, effectively splitting the remnants of the boreal forest into an eastern segment and a western segment in the Rockies. It is possible that the present day distribution of boreal forest floristic elements which overlap in the midwest (Larsen 1966) is a heritage of this Boreal separation? If the pattern given in Fig. 75 is correct, then the return of the *Pinus banksiana-Pinus resinosa* community to northwestern Minnesota must have been from the southeast as suggested by McAndrews (1966). If the close proximity of grassland and ice front persisted through the wasting of the Cochrane ice, then we also have a reason for extension of the known range of Plano type projectile points as far north as 63° in the vicinity of the 100th meridian (William Irving, personal communication).

The tentative sequence of events that then emerges at the outset of post-glacial time is thus as follows:

(1) An abrupt climatic change and rapid disappearance of a variety of boreal forest from large areas of the Dakotas, Nebraska, Iowa, Illinois, Wisconsin, Minnesota and eastward at the end of the Late Glacial.

(2) Rapid shift to grassland in the western part of the area once occupied by *Picea* and to mixed woodlands dominated by *Pinus banksiana* in eastern Minnesota and Wisconsin, and probably Michigan during Pre-Boreal time.

(3) In Boreal time, grassland extending nearly to the ice front in the Prairie Provinces, and to an oak-savanna-grassland boundary in central Wisconsin and eastern Minnesota, not far northeast of the present ecotone. It is probable that the *P. banksiana* mixed woods were found farther to the east during this time.

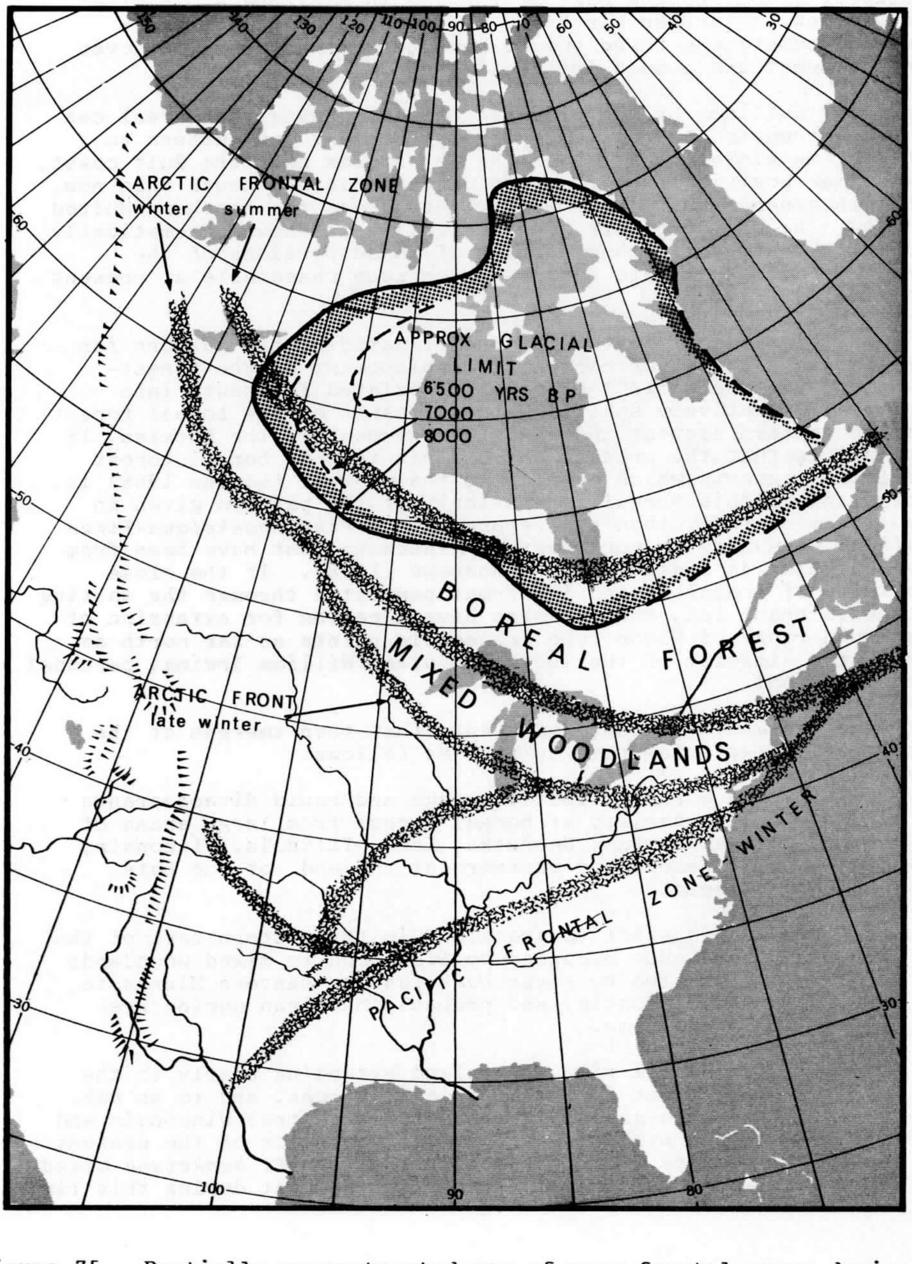

Figure 75. Partially reconstructed map of mean frontal zones during Cockburn-Cochrane time (*ca* 8,000 years ago). Glacial limit after Falconer *et al.* (1965).

Atlantic and Post-Atlantic Patterns

Rapid *in situ* wasting of the Cochrane ice must have occurred after about 8,000 years ago, as shown by the rough isochrones of the ice front in Fig. 75. These are based on field studies by the senior author and his colleagues who found that *Sphagnum* bogs started growing on the bottom of what had been pro-glacial Lake Kazan after its drainage about 6,000 years ago. Irving and Larsen (personal communication) found the apparent position of the ice front at that time in the vicinity of Dimma Lake. (61° 33' N lat., 101° 38' W long.) Nichols (1967) found necron mud farther south at Lynn Lake, Manitoba. (56° 50' N lat., 101° 03' W long.) Yet inside the Cochrane moraine which started to accumulate prior to 6,500 years ago. The large numbers of well-developed eskers with detailed features within the Cochrane moraine are strongly suggestive of *in situ* wasting. Even in a warm episode, such as the Atlantic was in central North America, there is a physical limit to the amount of net wastage in a year, and this limit is set by the amount of snowfall and the heat supply. It is possible that the snowfall in central Canada was as heavy in Atlantic time as in Valders time and even heavier than at present because more moisture could be present even with higher (though still below freezing) winter temperatures. Even neglecting the snowfall, if we take 70 Kcal/cm.^{2}-year as the total incoming radiation available, take the albedo over the glacier as .60, and the terrestrial back radiation as 20 Kcal/cm.^{2}-year, about 8 Kcal/cm.^{2}-year would be available for wastage. Assuming that 5 cm. of ice sublimated each year, there would be enough heat left to melt about 65 cm. of ice. Wasting at the rate of 70 cm./year, the Valders ice would last about 5,000 years, or until the end of Atlantic time!

Using a somewhat different calculation, we might reason that the available heat was considerably less than now, probably due to two reasons: (1) the altitude of the ice surface, and (2) the relatively high albedo of the ice. During the time of summer ablation, after the ice had been heated to 0° Centigrade at the surface, we calculate the net radiation to be about +15 Kcal available for ablation and heating. If convection and heating of the air are disregarded, the net radiation would be used soley for ablation. This simplified result would yield a maximum ablation rate. If 10% of the annual ice loss were sublimated, and the annual snowfall assumed to be 50 cm., the ice from Valders time would last about 3,500 years, or to at least 5,000 years B.C. Allowing some heat transfer to the air, more cloudiness, or heavier snowfall, still longer persistence of the ice might be expected.

The forest migrated northward as fast as the ice disappeared, probably even moving onto the moraine covered edges of the glacier. There is essentially no evidence for a tundra or treeless fringe between ice and forest (Nichols 1967). By early Sub-boreal time the forest border had migrated to a position about two degrees farther north in Keewatin than at the present (Bryson, Irving and Larson 1965) and there remained until about 1,500 B.C. Under the forest a podzol soil developed. The southern edge of the boreal forest in mid-America continued to lie somewhat northeast of its recent position through early Sub-boreal time (i.e., until 1,500 B.C.) (McAndrews 1966).

A reconstructed partial climatic map for early Sub-boreal time (5,000 to 3,500 years ago) is given in Fig. 76. Note that the most conclusive evidence for this time period is the position of the northern forest border.

A word should be said at this point emphasizing that the reconstructed maps are mean representations of the long term climate. It will be noted that similar patterns can be found in the modern series of daily or monthly mean charts (i.e., the winter pattern of Figure 73 is very similar to the mean map of February, 1952). This suggests that a change in the frequency of "anomalous" patterns alone is sufficient to explain the reconstructed patterns of the past.

These rather small known departures of the forest borders from the recent positions, and positions known for other more recent times (Bryson *et al.* 1965; Nichols 1967) indicate that from Atlantic time on the most fruitful approach to the variation of climate is in terms of small perturbations of the present climatic distribution. Returning then to the Atlantic period we should visualize the southern boundary of the boreal forest remaining fairly stationary while the northern boundary moved north to a position about two degrees north of its present position in central Canada. The tree line position farther northwest near the mouth of the MacKenzie River was probably nearly in its present position for Atlantic and post-Atlantic time since the controlling frontal zone is anchored there to the northern end of the Cordillera. Around 3,500 years ago the boreal forest shifted southwestward about two degrees, by migration in the south and by fire in the north, after which the forest did not regenerate. This, along with basal peat growth in Alaska [I (AGS) - 1, Heusser 1959] and palynological evidence of cooler weather in Finland (1-776, Trautman and Willis 1966) would suggest more meridional circulation of the atmosphere. It has been suggested that reformation of the permanent pack ice on the Arctic Ocean was associated with this change (Brooks 1949). This would certainly be consistent with the other evidence.

About 2,500 years ago, at the beginning of the sub-Atlantic, a further change occurred. The position of the boreal forest did not change much, but it became much wetter -- initiating the growth of blanket peat or "upland-muskeg" (WIS-1, Bender *et al.* 1965). A reasonable interpretation of the North American evidence, summarized briefly by Baerreis and Bryson (1965a), would suggest that the summers differed from the present primarily in the position of the upper-air anticyclonic eddy normally found over the Great Basin in summer. A displacement of this eddy northeastward would place the isentropic moist tongue, which normally brings rains to Arizona in summer (Bryson and Lowry 1955), along the Colorado Rockies, then curving eastward across the boreal forest of the prairie provinces and Ontario. Arizona should have been warmer under these circumstances (Woodbury 1961) and torrential thunderstorms should have

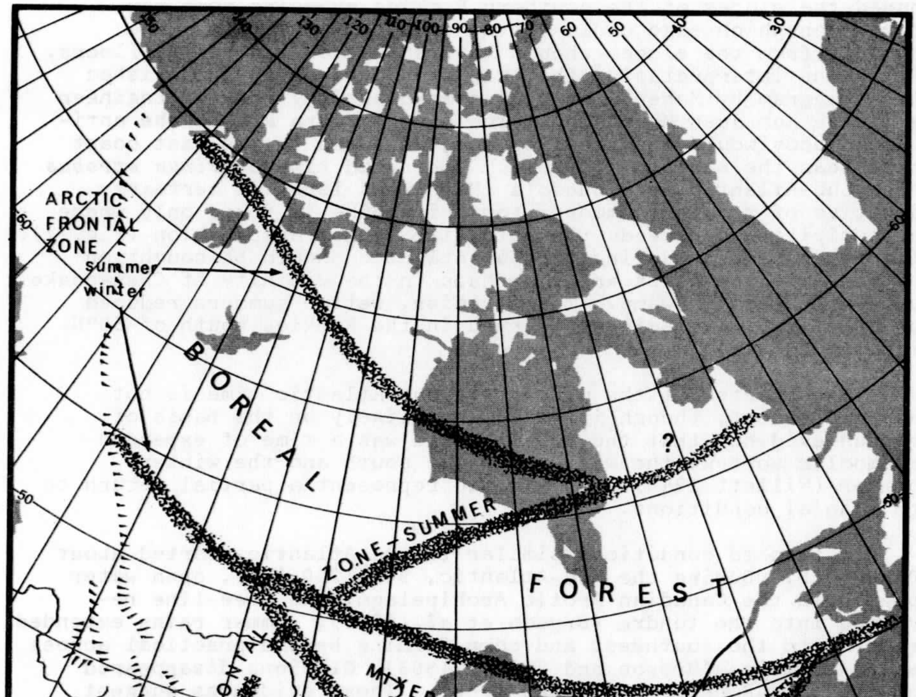

Figure 76. Partially reconstructed map of mean frontal zones during early Sub-boreal time (*ca.* 5,000-3500 years ago). Summer position of the Arctic front is the most certain feature of this time period.

denuded the slopes of the southern Rockies exposing more raw material on which sage could better compete with grass. The sediments from the slopes should have spread on the valley floors. This is one interpretation that can be placed on an unpublished pollen diagram by Maher (personal communication) for the Engineer bog in the San Juan Mountains. The dry, eastern arm of the anti-cyclonic eddy would then be displaced eastward to the east coast rather than the eastern mid-west. The rapid rise of *Pinus strobus* in the Sub-Atlantic in Minnesota (McAndrews 1966) is certainly indicative of moister summers, for white pine is found only where the precipitation exceeds the potential evapotranspiration (Fig.77). Evidence of drought during the Sub-Atlantic should be sought on the mid-Atlantic coast area, perhaps in the vicinity of Chesapeake Bay, or the Dismal Swamp. The cloudier, wetter summers reduced snow ablation and glaciers reformed in the Rockies south of 50°N (Richmond 1965).

The character of the winters in Sub-Atlantic time is not clear at present, though it would seem likely on the basis of European evidence that the Sub-Atlantic was a time of expanded circumpolar vortex, the westerlies far south and the winters stormier (Willett 1949). This would represent a partial return to Late Glacial conditions.

A return to conditions similar to the Atlantic started about 350-400 A.D. During the Neo-Atlantic, 900-1200 A.D., open water appeared in the Canadian Arctic Archipelago, the tree-line re-advanced into the tundra (Bryson *et al.* 1965), summer rains extended farther into the southwest and corn-farming became practical across the Great Plains (Bryson and Julian 1963). Glaciers disappeared from the U.S. Rockies (Richmond 1965). These evidences suggest weaker westerlies and more meridional circulation. The boreal forest probably expanded both south and north, while prairies shifted west at the expense of steppe. It would appear from a comparison of summer rainfall with strong westerlies, and summer rainfall with weak westerlies that a strip along the present forest-prairie ecotone between northwestern Minnesota and southern Wisconsin was somewhat drier (Fig. 78). There is pollen evidence for this in the *P. strobus* and *Nuphar* decline in Minnesota (McAndrews 1966).

The westerlies once again increased about 1200 A.D., terminating the Neo-Atlantic (Baerreis and Bryson 1965a). The northern edge of the boreal forest once more retreated southward (Bryson *et al.* 1965). The prairie peninsula climate, carried by the westerlies, opened a wider wedge of prairie eastward across Illinois and Indiana and the grassland communities were displaced eastward. Antelope increased in importance in relation to bison in the diet of the hunters of the western Dakotas (Lehmer 1966), bison became more important than deer in the meat diet of the Mill Creek people of northwestern Iowa (Baerreis and Bryson 1967), and some of the drought-stricken upper Republican farming people of Nebraska moved south to the Panhandle region of Oklahoma and Texas (Baerreis and Bryson 1965b) where the summer rainfall had increased. It would appear that the cultural impact of increased aridity in northern Illinois might have caused a breakdown of the contact between

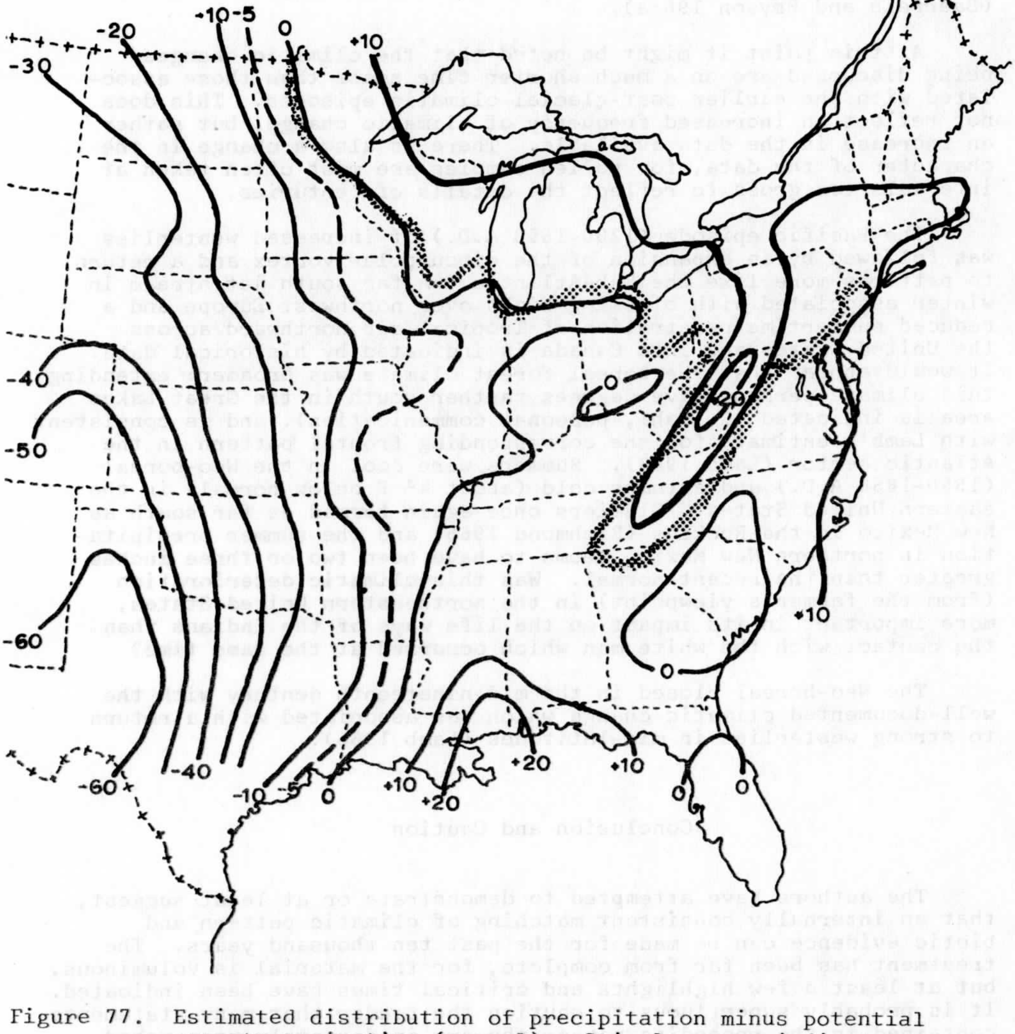

Figure 77. Estimated distribution of precipitation minus potential evapotranspiration (annual). Stipples zone indicates approximate southern limit of *Pinus strobus* (Trees, the Yearbook of Agriculture, 1949).

Aztalan and Cahokia and the abandonment of that recently established northern frontier outpost (Aztalan) of the Mississippian culture (Baerreis and Bryson 1965a).

At this point it might be noted that the climatic changes being discussed are on a much shorter time scale than those associated with the earlier post-glacial climatic episodes. This does not reflect an increased frequency of climatic change, but rather an increase in the data available. There is also a change in the character of the data, for pollen samples are most often taken at intervals too gross to reflect the details of centuries.

The Pacific episode (1200-1550 A.D.) of increased westerlies was followed by an expansion of the circumpolar vortex and a return to patterns more like the Sub-Atlantic. A far south jet stream in winter associated with blocking highs over northwest Europe and a reduced summertime penetration of Tropical air northward across the United States and into Canada is indicated by historical data. It would appear that the boreal forest climate was broader: extending this climate perhaps five degrees farther south in the Great Lakes area is indicated (E. Wahl, personal communication), and is consistent with Lamb's estimate for the corresponding frontal pattern in the Atlantic sector (Lamb 1963). Summers were cool in the Neo-boreal (1550-1850 A.D.) and autumns cold (about 4° F below normal) in the eastern United States. Glaciers once again formed as far south as New Mexico in the Rockies (Richmond 1965) and the summer precipitation in northern New Mexico seems to have been two or three inches greater than the recent normal. Was this climatic deterioration (from the farmer's viewpoint) in the northeastern United States, more important in its impact on the life ways of the Indians than the contact with the white man which occurred at the same time?

The Neo-boreal closed in the mid-nineteenth century with the well-documented climatic change which was associated with a return to strong westerlies in mid-latitudes (Lamb 1966).

Conclusion and Caution

The authors have attempted to demonstrate or at least suggest, that an internally consistent matching of climatic pattern and biotic evidence can be made for the past ten thousand years. The treatment has been far from complete, for the material is voluminous, but at least a few highlights and critical times have been indicated. It is probably superfluous to caution the reader that many statements contained in the preceding paragraphs are inadequately researched and possibly premature. It is believed, however, that the general pattern for North America is approximately as indicated. We hope that the readers will supply more evidence, better interpretation, and appropriate corrections.

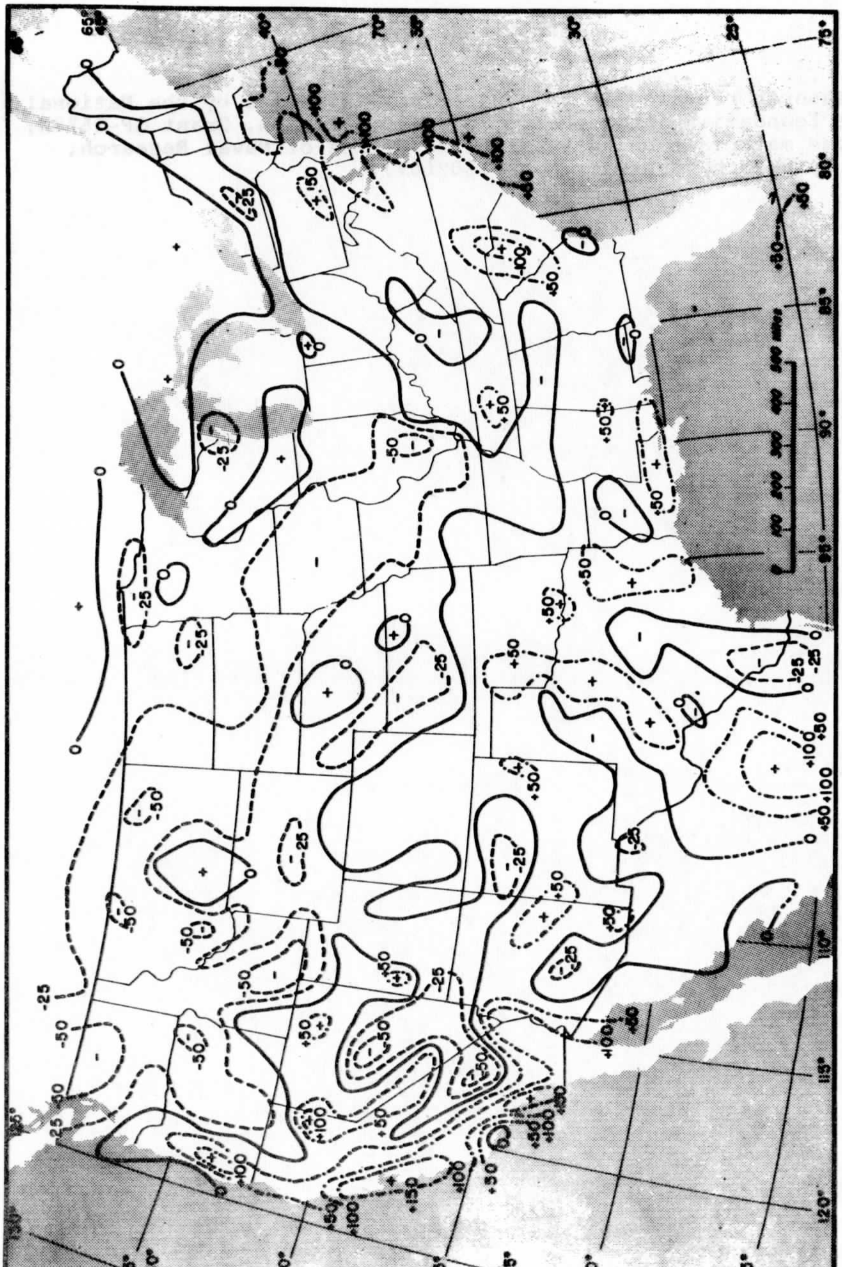

Figure 78. Precipitation with high zonal index minus precipitation with low zonal index. After Baerreis and Bryson (1967).

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4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

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

Information of the late- and post-glacial time is beginning to emerge from pollen diagrams, macrofossil deposits and faunal remains. Such evidence has been studied at tens of sites in North America. While each data site may be rather far removed from its closest neighboring site, meaningful synoptic meteorological patterns can be deduced from these data since airmass boundaries tend to be rather smooth, flowing lines, and certain features of these patterns are essentially "anchored" by geographical features. (U)

The modal climatic patterns for three periods were constructed. The first was the late-glacial period about 13,000-10,000 years B.P. (before present). The second was a time of minor

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(ABSTRACT cont.)

glacial advance, from 9,000-8,000 years B.P., and the third was early sub-Boreal time, about 5,000-3,500 years B.P. These particular times were chosen because ample evidence suggests that these times were significantly different from each other and different from the time both before and after the period in question. (U)

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

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

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Prof. Harley J. Walker
Dept of Geography
Louisiana State University
Baton Rouge, Louisiana 70803

Dr. David H. Miller
Dept of Geography
University of Wisconsin
Milwaukee, Wisconsin

Dr. Warren C. Thompson
Dept Meteorology & Ocean
U. S. Naval Post Grad. School
Monterey, California 93940

Dr. John R. Borchert
Department of Geography
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Robert M. Glendinning
Dept of Geography
University of California
Los Angeles, California 90024

Dr. Richard F. Logan
Dept of Geography
University of California
Los Angeles, California 90024

U. S. Fish & Wildlife Service
Dept of the Interior
Washington, D. C. 20360

Department of Geography
University of Washington
Seattle, Washington 98105

Directorate of Topography
& Military Engineering
Office Chief of Engineers
Gravelly Point
Washington, D. C. 20360

Waterways Experiment Station
Attn Geology Branch
U. S. Army Corps of Engineers
Vicksburg, Mississippi

U. S. Army Cold Regions Res & Eng Lab
P. O. Box 282
Hanover, New Hampshire

Central Intelligence Agency
Attn OCR/DD - Publications
Washington, D. C. 20505

Director
Office of Geography
Department of Interior
Washington, D. C. 20360

U. S. Weather Bureau
Attn Scientific Services Div
24th & M St. N.W.
Washington, D. C. 20360

Area Officer
Foreign Agricultural Service
U. S. Dept of Agriculture
Washington, D. C. 20360 2

Department of State
External Rsch Division
Room 8733
ATTN Chief, Government Branch
Washington, D. C. 20360 2

Dr. Paul A. Siple
Scientific Adviser
U. S. Army Research Office
Washington, D. C. 20360

Research Analysis Corporation
McLean, Virginia

Dr. Erhard M. Winkler
Department of Geology
University of Notre Dame
Notre Dame, Indiana

Dr. Richard J. Russell
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana 70803

Dr. Jonathan D. Sauer
Department of Geography
University of California
Los Angeles, California

Dr. John H. Vann
Dept of Geography & Geology
State University College
1300 Elmwood Avenue
Buffalo, New York

Dr. H. Homer Aschmann
Division of Social Science
University of California
Riverside, California 92502

Dr. Edward B. Espenshade
Department of Geography
Northwestern University
Evanston, Illinois 60201

Dr. John R. Mather
C. W. Thornthwaite Associates
Route #1, Centerton
Elmer, New Jersey 08318

Dr. Kirk H. Stone
Department of Geography
Univ of Georgia
Athens, Georgia 30601

Dr. David S. Simonett
Department of Geography
University of Kansas
Lawrence, Kansas 66044

Dr. James P. Latham
Prof & Chairman of Geography
Florida Atlantic Univ
Baco Raton, Florida 33432

Dr. Charles E. Olson
Department of Forestry
University of Illinois
Urbana, Illinois

Dr. William E. Benson
Program Director for Earth Sci
National Science Foundation
Washington, D. C. 20360

Dr. Frank Ahnert
Department of Geography
University of Maryland
College Park, Maryland 20740

Dept of Meteorology and
Oceanography
Naval Postgraduate School
Monterey, California 93940

Director
Arctic Institute of North America
1619 New Hampshire Avenue, N.W.
Washington, D. C. 20009

Dr. Jack P. Ruina
Director Advanced Research
Projects Agency
Office of the Sec of Defense
The Pentagon
Washington, D. C. 20360

ONR Branch Office
219 So. Dearborn
Chicago, Illinois 60601

Robert E. Frost
U. S. Army Corps of Engineers
Cold Regions Research and
Engineering Laboratory
Hanover, New Hampshire

Dr. Charles C. Bates
Assistant Civilian Director
U. S. Naval Oceanographic Office
Washington, D. C. 20390