November, 1980

MASTER

Progress Report to the Department of Energy
On Contract No. DE-ACO2-79EV 10097 Entitled
"Global Temperature Patterns 6000 Years Ago"

Thompson Webb III
Department of Geological Sciences
Brown University, Providence, RI 02912

INTRODUCTION

Work during year two of this contract has brought the project near to its goal of illustrating the climatic patterns of the mid-Holocene (5000 to 7000 years B.P.) over as broad an area of the northern hemisphere as possible. Maps of pollen, marine plankton, or lake-level data are now available from North America, Europe, Africa, and the North Atlantic. Maps of the pollen data from the Soviet Union are being prepared with other funding. Work is now in progress to reconstruct climatic estimates from as many of these data sets as possible. Precipitation estimates are available from pollen data in the midwestern United States and East Africa, and ocean-surface temperatures have been reconstructed from marine plankton data in the North Atlantic and eastern North Pacific Oceans (Appendix C).

The paleoclimatic maps for 5000 to 7000 years B.P. will show the patterns of temperature, precipitation, and atmospheric circulation for this mid-Holocene time during which the climate was warmer than it is today. These climatic patterns may be helpful in predicting some of the climatic changes during future climatic periods that are warmer than today.

SPECIFIC PROGRESS

The main work during the past year has been to assemble the data from pollen, marine plankton, and lake-levels required for producing northern hemisphere climatic maps for 5000 to 7000 years

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B.P. The research efforts of Webb (Brown University), Birks and Huntley (University of Cambridge), Ruddiman (Lamont-Doherty Geological Observatory, Columbia University), Street-Perrott (University of Oxford), and Wright (University of Minnesota) have all focused on this goal.

The work at Brown University has involved production of isopoll maps from Alaska, the western United States, and eastern Canada; initial climatic calibration of fossil pollen data from a core from Lake Victoria, East Africa; and improvement of the climatic calibration of a series of pollen cores in the midwestern United States.

P. Anderson, a graduate student at Brown, has completed pollen analysis of six cores from northwestern Alaska. Two cores have radiocarbon dates of over 20,000 years B.P. Her cores with radiocarbon-dated pollen evidence add to the meager and widely dispersed set of dated cores from Alaska and the Yukon. From this data base (Fig. 1), Anderson has assembled the available data for mapping the patterns of the seven dominant pollen types (Betula, Alnus, Picea, Gramineae, Cyperaceae, Salix, and Artemisia) for central and northern Alaska at 9000, 7000, 6000, 5000, and 3000 years B.P. Her maps show major changes in the vegetation over these 6000 years and are now being studied to see what climatic interpretations can be inferred. Anderson has a manuscript describing three of her cores (Anderson, unpubl. ms.) and is writing two other manuscripts to describe her other three cores and her pollen maps.

J. Overpeck, another graduate student at Brown, has updated the work of Webb et al. (1979) and mapped the available data for ten major pollen types in the western United States and southern British Columbia. His maps show widespread changes in several pollen types between 10,000 and 7000 years B.P. and between 7000 years B.P.

FOSSIL POLLEN SITES

- No Date
- △ Weak (1 Date or Problematic)
- ▣ Adequate (Some Interpretation Possible)
- ★ Good

Figure 1. Sites with pollen data used in mapping the patterns of pollen types at 9000, 6000, and 3000 years B.P.

and today. He is currently preparing a manuscript to describe the maps and the trends that they show. This work will then be integrated with the work of F. A. Street-Perrott, who has mapped the available lake-level data from the western United States (Appendix A and Webb et al., 1979).

T. Webb, with the help of L. Breindel and D. Gaudreau, has completed a preliminary set of isopoll maps for eastern Canada (Fig. 2). In September, 1980, Webb attended the AQQUA (Quebec Quaternary Assoc.) Meetings in Quebec City and discussed these maps with J. H. McAndrews (University of Toronto) and with P. Richard (University of Montreal). Both palynologists saw gaps in the data base and are sending pollen data from 15 new cores to help fill these gaps. Final preparation of the eastern Canadian maps is now awaiting incorporation of the new data.

The work in Labrador of H. E. Wright, Jr. (Appendix B) and of H. Lamb (University of Cambridge) has also contributed to the mapping of pollen data in eastern Canada (Lamb, 1980). H. Lamb is currently counting the pollen from new radiocarbon-dated cores in Labrador and has sent to Brown University modern pollen data from 70 lakes in Labrador. These data will aid in the climatic calibration of the eastern Canadian data.

The preliminary maps from eastern Canada show that spruce (Picea) pollen has increased in abundance both northwards and southward since 6000 years B.P. The southward movement is paralleled by a similar trend in fir (Abies) pollen and most likely reflects climatic cooling in southern Quebec and the Maritime provinces. Spruce spread into northern Quebec and Labrador 5000 to 4000 years B.P. just after the Laurentide ice sheet melted out of this region. The overall change for spruce pollen after 6000 years B.P. may indicate a broadening of the north-south temperature gradient in northeastern Canada and a steepening of this

Figure 2. Location of sites used in mapping the pollen types at past times in eastern Canada. Rectangular region is the area within which Wright will collect more cores to fill the gap between southeastern Labrador and the Laurentides in southern Quebec.

gradient to the south as a major frontal zone shifted southwards:

R. A. Lasleski, a graduate student at Brown who defended her Ph.D thesis (Laseski, 1981) on December 1, 1980; completed the pollen analysis of 59 surficial lake-sediments from East Africa. She then used these data to estimate former precipitation values from a 12,000-year core of fossil pollen from Pilkington Bay, Lake Victoria (Kendall, 1969). Her estimates show a broad peak in rainfall between 6000 and 9500 years B.P. (Fig. 3). Evaluation of these results is now in progress in light of the lake-level data compiled by F. A. Street-Perrott (Appendix A). D. A. Livingston (Duke University) supplied the lake sediment samples that R. A. Lasleski analyzed and kindly made his laboratory available to her for her pollen identification work.

The final main project at Brown University focused on improving the statistical methods used in calibrating pollen data in climatic terms. S. Howe (U.S. Bureau of Standards) worked at Brown during the summer of 1980 and presented an initial version of the improved methods in June, 1980, at the International Palynological Congress in Cambridge, England. A manuscript is now in preparation (Howe and Webb, in prep.) that describes the steps in calibration and incorporates a new step for testing the spatial autocorrelation of the residuals from the multiple regression equation. Using the new procedures, Webb has prepared a new set of precipitation maps for 9000, 7000, 6000, 5000, and 3000 years B.P. for the midwestern United States. These maps show the pattern of decreased precipitation at 6000 years B.P. from Minnesota westwards.

Appendices A through D describe the specific research progress of Street-Perrott (Appendix A), Wright (Appendix B), Ruddiman (Appendix C), and Birks and Huntley (Appendix D). The data compiled, analyzed, and mapped by each of these workers will be

Figure 3. Preliminary estimates of mean annual rainfall from a 14,000 year record in Pilkington Bay, Lake Victoria, Uganda. Kendall (1969) did the pollen analysis on the core and Laseski (1981) did the calibration.

incorporated by Webb during year three into hemispheric maps of the climates 9000, 7000, 6000, 5000, and 3000 years B.P.

Street-Perrott (Appendix A) has updated her computer files of past lake-level data and produced new maps for Africa (Perrott and Street-Perrott, unpubl. ms.). She is also co-authoring with G. I. Smith (U.S. Geological Survey) an article on past lake-levels for lakes and playas in the western United States.

Wright's work in Labrador was briefly summarized earlier in this report and is detailed in Appendix B.

Ruddiman (Appendix C) has compiled a list and map of all ocean cores with radiocarbon dates. A subset of 40 of these cores have counts of planktonic microfossils, and from this subset, 27 cores have yielded data contrasting the ocean surface temperatures between 6000 years B.P. and today. Initial maps of these data show that 6000 years B.P. the temperatures were higher in mid- and high-latitudes but lower in low latitudes than temperatures today.

Birks and Huntley (Appendix D) with DOE funding were able to expand their mapping of pollen data in northwest Europe into eastern and southern Europe. Their maps are now being prepared for publication in a book to be published by the Cambridge University Press. From their pollen maps, they have inferred the patterns of past vegetation regions and used the changes in these patterns to infer past changes in climate. They conclude that since 5000 years B.P. temperatures have increased in southern Europe but decreased in the north with the biggest changes in eastern Europe.

With the completion of much of this work by March, 1981, we will be able to focus the main effort of the project on producing hemispheric maps to synthesize the diverse research supported so far. These maps will update the map of Kellogg (1978) that showed some of the inferred climatic conditions for 5000 to 7000 years B.P.

REFERENCES

- Anderson, P.M. A palynological analysis of lake sediments from the Alaskan North Slope. Submitted to Arctic and Alpine Research.
- Kellogg, W.W., 1978. Global influences of mankind on climate. In J. Gribben (ed.) Climatic Change, Cambridge University Press, Cambridge, pp. 205-227.
- Kendall, R.L., 1969. An ecological history of the Lake Victoria Basin. Ecological Monographs 39: 121-176.
- Lamb, H.F., 1980. Late Quaternary vegetational history of southeastern Labrador. Arctic and Alpine Research 12: 117-135.
- Laseski, R.A., 1981. Modern pollen data and Holocene climatic change in East Africa; Ph.D. Thesis, Brown University.
- Perrott, R.A. and F.A. Street-Perrott. New evidence for a Late Pleistocene wet phase in northern intertropical Africa. Palaeoecology of Africa 13 (submitted for publication).
- Webb, T. III, F.A. Street, and S. Howe, 1979. Precipitation and lake-level changes in the West and Midwest over the past 10,000 to 24,000 years. Final Report prepared for Lawrence Livermore Laboratory, Livermore, CA; 102 pp.

APPENDIX A

Global Temperature Patterns 6000 Years Ago:
African and Western North American Lake-level Changes

Progress Report, November, 1980

F. Alayne Street-Perrott
School of Geography
Oxford, England OX1 3TB

The data bank at Oxford of radiocarbon-dated evidence of past lake-levels has been significantly updated. Bibliographic searches have yielded a modest number of new sites with data on past lake levels. The data on the site location, elevation, radiocarbon dates, and lake levels have been key punched and added to the computer files. Neil Roberts (University of Oxford) has thoroughly reviewed the evidence from the Near East and added his information to the data base, and Gilbert Peterson (University of Wisconsin) has provided information on past lake-level changes in the Soviet Union.

Two major efforts are now in progress to publish the assembled information from Africa and the Near East and from the western United States. The African data were updated and presented at the joint U.S./France Workshop in Gif-sur-Yvette (September, 1980). Key maps show uniformly high lake levels for 8000 to 9000 years B.P. (Fig. 1), a moderate drop in some lake levels by 5000 to 6000 years B.P. (Fig. 2), high lake-levels in central Africa but low lake-levels in northeastern Africa and Saudi Arabia and in eastern and south Africa by 4000 to 5000 years B.P. (Fig. 3), and mostly low lake levels today (Fig. 4) and 1000 to 2000 years B.P. (Fig. 5). Some of this evidence has been described in Perrott, R. A. and Street-Perrott, F. A., "New evidence for a Late Pleistocene

Figure 1. Lake-levels at 8000 to 9000 years B.P. Solid circle denotes high water levels, open circle denotes intermediate water levels, triangles denote low water levels.

Figure 2. Lake levels at 5000 to 6000 years B.P. Solid circle denotes high water levels, open circle denotes intermediate water levels, triangles denote low water levels.

Figure 3. Lake levels at 4000 to 5000 years B.P.. Solid circle denotes high water levels, open circle denotes intermediate water levels, triangles denote low water levels.

Figure 4. Lake levels at 0 to 1000 years B.P. Solid circle denotes high water levels, open circle denotes intermediate water levels, triangles denote low water levels.

Figure 5. Lake levels at 1000 to 2000 years B.P. Solid circle denotes high water levels, open circle denotes intermediate water levels, triangles denote low water levels.

wet phase in northern intertropical Africa", Palaeoecology of Africa 13 (submitted for publication).

The evidence on the lake-level data from the western United States will be appearing in a chapter on "Pluvial Lakes" by F. A. Street-Perrott and G. I. Smith for the 1982 U.S. INQUA volume on the Late Wisconsin edited by Steve Porter. These maps show that the lake levels in the western United States had decreased from generally high levels 13,000 to 12,000 years B.P. to low levels 6000 to 5000 years B.P. A few lakes in Nevada and California have shown a rise in lake levels to intermediate levels since that time.

APPENDIX B

Climatic History of Southeastern Labrador: Contribution
to Understanding Global Temperature Patterns 6000 Years Ago

Progress Report, November 1980

Herbert E. Wright, Jr.
Limnological Research Center
University of Minnesota, Minneapolis, MI 55455

Field work in Labrador and associated laboratory studies at the University of Minnesota have yielded the following results:

1. The ice sheet retreated from southeastern Labrador and the Labrador east coast about 10,000 years ago but persisted on the Labrador-Quebec plateau until about 6,000 years ago, according to radiocarbon dates on basal lake sediments.
2. Pollen studies of lake sediments indicate that tundra vegetation prevailed in southeastern Labrador from the time of deglaciation until 6,000 years ago. Fir and white birch trees then invaded the area along with spruce, indicating a shift from cold to temperate conditions without an intermediate or transitional stage that would be suggested by the modern forest zonation of eastern Canada (tundra to spruce forest to fir forest). The relatively high pollen percentages of fir at some sites indicate the dominance of this tree in the forest from 6,000 to 5,000 years ago, implying a climate warmer than that of today, for in the modern forest of the area fir is a minor constituent and is represented by only a few percent pollen. Fir forests are dominant today in parts of Newfoundland and elsewhere in the Maritime Provinces south of Labrador.
3. The interval of fir dominance (6,000 - 5,000 years ago) is contemporaneous with the latter part of the warm Hypsithermal

interval, expressed in the Middle West by the eastward shift of the prairie/forest border. During the earlier part of the Hypsithermal (8,000 - 6,000 years ago) southeastern Labrador still had tundra vegetation, presumably because of the periglacial effects of the still-persisting ice sheet on the plateau to the northwest. A related factor was the barrier to tree immigration provided by the periglacial climate: spruce and fir had reached the Quebec City area from the south by 10,000 years ago but their migration along the north coast of the Gulf of St. Lawrence to southeastern Labrador was delayed by the periglacial climatic barrier, despite the fact that the climate may have been warmer than even south of the Gulf. When the waning ice mass disappeared by 6,000 years ago, fir rapidly immigrated into southeastern Labrador along with spruce.

4. After the fir maximum in southeastern Labrador the forest composition changed to black spruce, which has persisted until today as the dominant tree type, with relatively minor representation of fir, white spruce, and birch, although these latter trees are relatively common on the lower elevations fringing the central plateau of southeastern Labrador. The relations imply cooler climatic conditions after 5,000 years ago. A secondary factor in the vegetation succession is the progressive accumulation of raw humus on the forest floor, favoring black spruce over more nutrient-demanding trees. As much as a half meter of raw humus now occurs over broad areas of upland, and peat-filled wetlands in the low areas seem to be spreading up the gentle hill slopes. This progressive paludification of the landscape, presumably favored by the cool, moist climate that inhibits microbial decomposition on the forest floor, is also favored by the low incidence of forest fire. When fire does occur it burns only a portion of the forest floor, and regeneration of black spruce after fire is extremely slow in this area, apparently because the burned humus does not

retain enough moisture for spruce-seed germination. Only after several decades of moss growth on the forest floor are conditions favorable for extensive spread of black spruce from the scattered trees that have become established. Thereafter the forest closes rapidly over the moss- and lichen-covered forest floor, primarily by the process of layering -- low branches of black spruce, partially buried by the growth of mosses, curve upward to become separate tree trunks. The forest may continue thus for several centuries until the next fire.

5. The paleoclimatic sequence will be quantified as a first approximation by the application of transfer functions based on pollen surface samples collected from a transect of 70 lakes in areas of known climate ranging from the tundra of northern Labrador to the forest-tundra and lichen woodland of central Labrador to the closed black spruce forest of the southeast, supplemented by other surface samples available elsewhere in the Maritime Provinces. Application of the transfer-function technique must be tempered by an understanding of the ecological controls on tree distribution and on factors of delayed tree immigration, as discussed above.

6. The vegetation sequence in southeastern Labrador is reflected indirectly in the chemistry of lake sediments. Stratigraphic analyses of pigments and tannins indicate the proportion of organic matter washed in from the vegetated hill slopes compared to that produced in the lake by aquatic plants. Bulk samples of sediment were chemically separated into mineral and organic components, so that separate analyses could be made of those elements that are particularly sensitive to conditions of acidity or oxygen content in soils or lake sediments or are biologically active (iron, manganese, aluminum, silicon). The conspicuous stratigraphic changes in the various chemical components

can be correlated with the events on the surrounding drainage basin as recorded by the pollen sequence. Diatom analyses of the same lake sediments will be made to investigate further the history of lake conditions in the context of watershed changes.

The following publication appeared in print during the year: Lamb, H.F., 1980, Late Quaternary vegetational history of southeastern Labrador. Arctic and Alpine Research, v. 12, p. 117-135. Additional publications are in preparation, as well as three doctoral dissertations. The work has been supported additionally by grants from the Smithsonian Institute, the National Geographic Society, the National Science Foundation, and partial student stipends from the University of Minnesota and Cambridge University.

APPENDIX C

Paleo-oceanographic Reconstruction of Global Ocean Sea-Surface Temperatures at 6000 Years before Present

Progress Report, November 1980

William F. Ruddiman
Lamont-Doherty Geological Observatory
Palisades, New York 10964

INTRODUCTION

The oceans, as a major component of the global circulation, are integral to any attempt to reconstruct the earth's climate 6000 years ago. The oceans receive almost all of the incoming solar radiation and transport significant amounts of heat poleward, surrendering heat and moisture to the air and ultimately to the continents. Particularly critical to climate 6000 years ago is the question of whether, in a given area, the air-sea temperature differences were larger, smaller, or similar relative to today. This difference in part fixes the transfer of oceanic heat and moisture to the air and land.

The goal of this research is to reconstruct sea-surface temperatures 6000 years ago in critical regions of the Northern Hemisphere oceans.

RESEARCH ACCOMPLISHMENTS

The report in this Appendix summarizes the research accomplished during our first year of significant DOE funding. Note that in many cases we have actually compiled data for the oceans across the entire globe, when we had proposed a compilation only for the Northern Hemisphere oceans.

1. Compilation of ¹⁴C Dates. Our global compilation of all

^{14}C dates in deep-sea cores has yielded 739 dates in 226 cores, whose locations are shown in Figure 1. The following data for each core are punched on computer cards: core name, latitude, longitude, water depth, top of interval dated, bottom of interval dated, age, dating error, laboratory, and lab number. From this list, we have culled those cores with radiocarbon dates which closely limit the 6000-year level. These 27 cores are shown in Figure 2.

2. Compilation of cores with Biotic Census Counts. We have also compiled a list of all cores containing published (or unpublished but in-hand) census counts on planktonic microfossils that can be processed for transfer-function estimates of sea-surface temperature. This list includes 40 cores with relatively detailed counts spaced at intervals of 2000 years or less (most are about 1000 years); it also includes another 25 cores with wider time increments between census counts.

3. Cores for Inclusion in 6000-Year Map. The two compilations listed above have yielded a third: those cores with both adequate ^{14}C dates and close-spaced census counts. The 12 optimal cores that fall out of this analysis are mapped in Figure 3, along with another 15 cores with close-spaced counts and other stratigraphic control adequate to define the 6000-year level but without fully detailed ^{14}C dating. Several of these cores were analyzed for faunal counts during the last year of DOE funding.

For these 27 cores, we have mapped in Figures 4 and 5 the observed difference in estimated August and February temperature between the 6000-year level and the core top. We stress that these values are uncorrected for bioturbation effects, which may have significantly altered many of the values mapped.

In general, the 6000 B.P. ocean temperatures (uncorrected) in the North Atlantic look little different from today. The

Figure 1. Cores with at least one ^{14}C date.

Figure 3. Cores with high-quality ^{14}C dates and with census counts and temperature estimates at intervals of less than 2000 years. Boxes indicate primary cores with highest quality ^{14}C control; triangles indicate secondary cores with other control adequate to fix the 6000-year level.

Figure 4. Difference in February sea-surface temperature 6000 years ago vs. today (+ means 6000 years ago was warmer).

Figure 5. Difference in August sea-surface temperature 6000 years ago vs. today (+ means 6000 years ago was warmer).

values are systematically warmer along the east coasts of North America and Greenland and in cores in the South Atlantic off southwest Africa. They are slightly cooler in one area at approximately 40° - 45° N, 30° - 35° W and another along the Canaries Current off Saharan Africa. Most of the other temperature departures lie within or on the margin of the error of estimate of the method and thus are not highly significant. However, coherence from core to core within a region and from sample to sample within a core is evidence that some of these departures may be meaningful. Adjusting for the effects of bioturbation will alter the amplitude of some of these anomalies.

To address the question of whether an oceanic "climatic optimum" (an ocean warmer than today) existed at any time during the last 10,000 years, we have also examined in these same cores the basic pattern of ocean temperature climate change for the last 10,000 years. Most North Atlantic cores show a well-defined peak of oceanic warmth centered at about 3000 years ago and often marked by statistically significant positive temperature departures from today. This period appears to be a primary candidate for a warm postglacial ocean.

Most of the cores outside the North Atlantic, as well as some within, contain a well-defined temperature maximum at about 8000 years ago. This warmth is most marked along the east coast of Greenland, the east and west coasts of North America, and the west coast of Africa. Oceanic warmth equivalent in age to the classical continental climate optimum 6000 years ago is limited to scattered cores in the temperate latitudes (Fig. 4,5). And in many cores, a short cooling roughly 6000 years ago bisects the two warmer intervals before and after that time.

We thus arrive at the very preliminary conclusion that most of the North Atlantic Ocean at 6000 B.P. was not significantly

different in temperature from today, but that several locations show significantly greater warmth about 8000 and 3000 years ago. These generalized observations and conclusions are highly preliminary and need substantial testing, evaluation and verification for each of several critical ocean areas. This we propose to accomplish in the next year.

APPENDIX D

Global Temperature Patterns 6000 Years Ago: Europe

Progress Report, November 1980

B. Huntley and H.J.B. Birks
University of Cambridge
Cambridge, England CB2 3EA

INTRODUCTION

The primary data base is now assembled and contains data for 840 locations in the area being investigated. Data have been compiled for 55 pollen taxa, including all major tree, shrub, and herbaceous pollen taxa. Data are available for 623 surface sample localities and for 278, 252, and 219 sites at 5K, 7K, and 9K B.P., respectively. Isopollen maps are in preparation for most of the pollen taxa, and have been completed for six of the major trees. Copies of these completed maps are included. Maps showing the localities of the sites available at 5K, 7K, and 9K are also included (Fig. 1 to 3).

In addition to mapping individual pollen taxa, maps have been prepared for groups of taxa which are regarded as characterizing particular broad vegetation-types today. Four such indicator groups are considered here and are termed Mixed-deciduous, Mediterranean, Steppe, and Montane. The last of these is perhaps better termed Montane/Boreal since although all the taxa it includes are characteristic of the Montane coniferous forests of the European mountains, one of them (spruce) is also the primary constituent of the boreal coniferous forests of Fennoscandia and Russia. Using the surface sample maps for these indicator-groups, threshold pollen values have been established which coincide closely with the limits of the modern vegetation-types they characterize, and iso-

Figure 1. Sites with pollen data for 5000 years B.P.

Figure 2. Sites with pollen data for 7000 years B.P.

Figure 3. Sites with pollen data for 9000 years B.P.

pollen lines for this threshold value have then been drawn on these maps and on the 5K, 7K, and 9K B.P. maps. These isopolls are a geographic analogy of stratigraphic zone lines used by palynologists. Furthermore, they indicate the position of major ecotones today, and presumably also in the past. Maps showing the positions of these at the four time points are included, and may be regarded as provisional isochrone maps for these major ecotones.

By combining on one map the threshold-value isopolls for the four indicator groups at a particular time, we have the beginnings of a reconstructed vegetation map based upon pollen evidence. When this work is done for the surface sample data, and certain general rules of precedence are followed that simplify the resulting pattern, a reconstructed modern potential natural vegetation map results that agrees remarkably well with vegetation maps of Europe. This agreement encourages us to consider maps similarly constructed for 5K, 7K, and 9K B.P. as giving some broad indication of the former paleovegetation patterns. Clearly the exclusion of important taxa such as Betula and Pinus, whose extent and importance were greater in the past, must be remembered when examining these maps, and there is scope for further refinement of the maps using information from these and other taxa that have been excluded.

THE MAPS

Corylus spp. are large shrubs or small trees found characteristically in mixed-deciduous forests. The surface-sample map shows their pollen to be most abundant in the British Isles but occurring widely from southern Fernoscandia to the northern edge of the Mediterranean basin (Fig. 4). At 5000 B.P. their pollen was more abundant over large areas of Europe and their range extended both further north and further south (Fig. 5). At 7000 B.P. the range was similar to that at 5000 B.P., but high pollen values

Figure 4. Isofrequency contours for the contemporary distribution of the percentages of hazel (*Corylus*-type) pollen in surficial sediments

Figure 5. Hazel pollen at 5000 B.P.

were extensive in western Europe (Fig. 6). At 9000 B.P. the range was less extensive northwards and was fragmented even on the European mainland (Fig. 7). The close packing of the isopolls at 9000 B.P. accords with the rapid migration and expansion of range occurring at this time.

Tilia spp. are also characteristic of mixed-deciduous forests. Their pollen is sparse in the surface samples but extends north to northern England and southern Fennoscandia (Fig. 8). At 5000 B.P. Tilia pollen was widespread and reached values of five percent over extensive areas (Fig. 9). Their range at this time was, however, very similar to that seen today. At 7000 B.P. the range was less, primarily in the north and west, and pollen values were lower (Fig. 10), whereas at 9000 B.P. Tilia pollen was sparse except in southern and eastern Europe (Fig. 11).

Fraxinus excelsior and its close relatives are again mixed-deciduous forest trees whose pollen is sparse in surface samples. Their pollen is, like Corylus, found most abundantly and consistently in north-west Europe at the present (Fig. 12). At 5000 B.P. their pollen was found extensively across the northern European mainland, but in Britain only in England and Wales, and pollen values were lower than today (Fig. 13). At 7000 B.P. their range was even more eastern and southern (Fig. 14), and at 9000 B.P. their pollen is found consistently only in the southern Alps and the eastern Balkans (Fig. 15).

Fagus spp. are trees of mixed-deciduous forests with a primarily south-eastern tendency in their distribution. This is reflected by the surface-sample map which shows the highest pollen values in eastern Europe, and a range which includes only extreme southern Scandinavia and southern Britain (Fig. 16). At 5000 B.P. the range is much more clearly south-eastern, and the tendency of Fagus to be especially abundant in montane deciduous and conifer-

Figure 6. Hazel pollen at 7000 B.P.

Figure 7. Hazel pollen at 9000 B.P.

Figure 8. Isofrequency contours for the contemporary distribution of the percentages of basswood (*Tilia*) pollen in surficial sediments.

Figure 9. Basswood pollen at 5000 B.P.

Figure 10. Basswood pollen at 7000 B.P.

Figure 11. Basswood pollen at 9000 B.P.

Figure 12. Isofrequency contours for the contemporary distribution of the percentages of ash (*Fraxinus excelsior*) pollen in surficial sediments.

Figure 13. Ash pollen at 5000 B.P.

Figure 14. Ash pollen at 7000 B.P.

Figure 15. Ash pollen at 9000 B.P.

Figure 16. Isofrequency contours for the contemporary distribution of the percentages of beech (*Fagus*) pollen in surficial sediments.

Figure 17. Beech pollen at 5000 B.P.

hardwood forest types is reflected by the close association of high pollen values with the major European mountain chains (Fig. 17). At 7000 B.P. Fagus is very restricted, occurring in the northern Balkans and around the northern Adriatic (Fig. 18), and at 9000 B.P. pollen values of two percent are found consistently only in the Balkans (Fig. 19).

Abies spp. are characteristic of montane coniferous and conifer-hardwood forests, and this is reflected by the association, on the surface-sample map, of Abies pollen with the European mountains (Fig. 20). At 5000 B.P. Abies pollen is also associated with the mountains, but values are higher and the range more continuous (Fig. 21). At 7000 B.P. the range is much smaller (Fig. 22), and at 9000 B.P. pollen is found consistently only in the southern Alps (Fig. 23).

Picea spp. are also primarily montane conifers, but P. abies is the major component of the boreal coniferous and northern conifer-hardwood forests of Europe today. This is well reflected by the surface-sample map (Fig. 24). At 5000 B.P. the northern range is much restricted eastwards, and in the south high values occur in the eastern Balkans (Fig. 25). At 7000 B.P. the northern range is again reduced (Fig. 26), and at 9000 B.P. there is no consistent presence of Picea pollen in northern Europe (Fig. 27). By 9000 B.P. the southern range is also reduced eastwards.

The isochrone map for the Mediterranean indicators shows an overall trend of northward and westward movement from 9000 B.P. to the present (Fig. 28). This is in marked contrast to that for the mixed-deciduous indicators (Fig. 29). These had a limit at 9000 B.P. similar to today except in central Scandinavia where they extended further north. At 5000 and 7000 B.P., however, their limit lay much further north in Fennoscandia although it was little different in the east. The Steppe indicators were widespread through-

Figure 18. Beech pollen at 7000 B.P.

Figure 19. Beech pollen at 9000 B.P.

Figure 20. Isofrequency contours for the contemporary distribution of the percentages of fir (*Abies*) pollen in surficial sediments.

Figure 21. Fir pollen at 5000 B.P.

Figure 22. Fir pollen at 7000 B.P.

Figure 23. Fir pollen at 9000 B.P.

Figure 24. Isofrequency contours for the contemporary distribution of the percentages of spruce (*Picea*) pollen in surficial sediments.

Figure 25. Spruce pollen at 5000 B.P.

Figure 26. Spruce pollen at 7000 B.P.

Figure 27. Spruce pollen at 9000 B.P.

Figure 28. Isochrone map for the northern limit of the group of pollen types indicating Mediterranean vegetation.

out southern Europe, except the southern Balkans, at 9000 B.P. but by 7000 B.P. their pollen values did not consistently exceed the threshold value of 25 percent anywhere in Europe (Fig. 30). At 5000 B.P. Steppe had returned to a small area of the northern Balkans and at the present-day is locally extensive in the Balkans. At 9000 B.P. the Montane indicators were present in the Balkan mountains and sparsely in the Alps (Fig. 31). By 7000 B.P. they had expanded around the Alps and this continued at 5000 B.P. Today they are less extensive, especially in the south-east. In northern Europe this group is represented only by Picea abies and the behavior is as expected; the group is not present at 9000 B.P., local in the east at 7000 B.P., extensive in the east by 5000 B.P., and today has extended throughout most of Fennoscandia.

The reconstructed vegetation maps provide an alternative viewpoint to the indicator-group isochrone maps. In constructing the maps, we found that certain rules of precedence were needed in establishing which group is in which broad region. These rules much simplify the patterns that appear on the maps. For the maps shown (Fig. 32 to 35), the most southerly group, Mediterranean, is given precedence over the Steppe group, but the Montane group supercedes both of these. Both the Steppe and Mediterranean groups have precedence over the Mixed-deciduous group. In central Europe the Montane group also has precedence over the Mixed-deciduous group, since the mixed conifer-hardwood zone in the mountains is on too small a spatial scale to be mapped here. In northern Europe, however, the area within the threshold for both the Mixed-deciduous and Montane groups is recognized as mixed conifer-hardwood zone. The areas in the north beyond the threshold for either the Mixed-deciduous or Montane groups, whichever is the northernmost, are taken to be treeless tundras.

Seven vegetation units are distinguished on the map based on

Figure 30. Isochrone map for the group of pollen types indicating the growth of steppe vegetation.

Figure 31. Isochrone map for the group of pollen types indicating the growth of montane vegetation.

Figure 32. Pattern of reconstructed vegetation from samples of the modern-day pollen.

Figure 34. Pattern of reconstructed vegetation from pollen samples dated to 7000 years B.P.

Figure 33. Pattern of reconstructed vegetation from pollen samples dated to 5000 years B.P.

Figure 35. Pattern of reconstructed vegetation from pollen samples dated to 9000 years B.P.

surface samples (Fig. 32). Tundra in the north is succeeded southwards by mixed-deciduous forest in the west, whereas in the east boreal conifer and mixed conifer-hardwood forests occur. Montane conifer forest is extensive in central Europe with Steppe to the south in the Balkans. Mediterranean evergreen forests are extensive in southernmost Europe.

At 5000 B.P. there was no boreal conifer forest as we know it today, and tundra was succeeded southwards by mixed-deciduous forests throughout (Fig. 33). However, there was in eastern Fennoscandia an area of mixed conifer-hardwood forest surrounded by mixed-deciduous forests on its northern, western, and southern margins. The areas of Steppe and of Mediterranean evergreen forest were both less than today.

At 7000 B.P. the areas of mixed conifer-hardwood and Mediterranean evergreen forests were further reduced, and there was no Steppe (Fig. 34). The area of Montane conifer forest was also reduced in the east, and mixed-deciduous forest was at its most extensive.

At 9000 B.P. the northern margin of the forests was displaced southwards, and tundra, including areas of residual ice cap in Fennoscandia, extended much further south (Fig. 35). There was no conifer-hardwood forest. Montane conifer forest was local in central Europe though extensive in the east. A broad zone of Steppe vegetation extended throughout southern Europe, isolating the Mediterranean evergreen forest in the extreme south and cutting off a small area of mixed deciduous forest in the Southern Balkans.

DISCUSSION

The maps of individual taxa, especially the four mixed-deciduous forest taxa, illustrate the essentially unique and independent behavior of the taxa. Clearly vegetational assemblages have

not been constant during the Holocene, and vegetation has not reacted to climatic change in any coordinated way; rather each taxon has reacted according to its own individual tolerance, migrational abilities, etc. These maps also illustrate the enormous influence that anthropogenic forest clearance has had in Europe since 5000 B.P., both in the lowlands and in the mountains (e.g., Abies). Furthermore the maps show that taxa which today are characteristic of particular broad vegetation types may have had glacial refugia which were widely separated.

The interpretation of these maps for individual taxa requires detailed consideration of the reproductive biology and autecology of the taxa. Edaphic, anthropogenic, climatic, and other factors often need to be taken into account, and migrational lag resulting from the position and number of the refugia should not be overlooked. Even the longevity of individuals can be important; for example Corylus, a short-lived small tree, shows a southward retreat since 5000 B.P. (Fig. 4 and 5) whereas Tilia, a very long-lived tree, though much reduced in abundance since 5000 B.P. extended over a range which is little changed (Fig. 8 and 9). Work carried out on the reproductive biology of T. cordata has shown that it is unable to reproduce, except in very favorable years, in the northern part of its range due to inadequate summer warmth. At 7000 B.P., however, it expanded into these areas and must therefore have been capable of sexual reproduction. In effect its potential range has, like that of Corylus, been reduced southwards since 5000 B.P., but it has survived locally, as a result of its ability to sucker and its resulting virtual immortality, outside its present potential range.

Despite these, and many other problems, the indicator-group isochrone and reconstructed vegetation maps, summarizing as they do the behavior of a number of taxa, are more appropriate for climatic

interpretation. The most important feature is the absence of any period of parallel climatic change throughout Europe, rather the climatic patterns have changed as a result of distinct and sometimes opposing changes in different parts of Europe. The movement of the Mediterranean-group-threshold implies continuous northward and westward expansion of the area with a Mediterranean climate since 9000 B.P. (Fig. 28), whereas the northward movement of the mixed-deciduous group threshold between 9000 B.P. and 7000 B.P. in Fennoscandia and its subsequent retreat after 5000 B.P. implies a climatic change there, with conditions becoming more and then less favorable for these trees (Fig. 29). The northern limit for the Mediterranean group is probably determined principally by summer temperatures and to a lesser extent by winter rainfall, whereas the northern limit for the mixed-deciduous group is probably almost solely controlled by summer temperatures and the resulting length of the growing season.

The extent of the Steppe group is determined principally by rainfall, but also by summer temperatures and the resulting low precipitation/evaporation ratio (Fig. 30). The most difficult group to characterize climatically is the Montane group (Fig. 31). In central Europe the types in this group form an altitudinally determined zone above the limits of the deciduous taxa, but the factors restricting their descent into the lowlands are not obviously climatic. The increased precipitation/evaporation ratio in the mountains may be important, however. In Fennoscandia the extent of Picea, and its later Holocene expansion, may be related to a relatively high precipitation/evaporation ratio, or to other factors such as anthropogenic influence, soil changes, or migrational lag.

Using these broad guidelines, it is clear that at 9000 B.P. climate was cooler and more continental than today, with a zone of

aridity in the northern part of the Mediterranean basin. The absence of Picea in Fennoscandia and the restriction of Montane conifers in central Europe similarly suggests reduced precipitation. By 7000 B.P. the climate was much less arid but only a little warmer in the south, whereas in the north, there was increased precipitation and much warmer temperatures. At 5000 B.P. warming continued in the south, but precipitation was reduced in the south-east. In the north temperatures changed little, but precipitation further increased. Since 5000 B.P. warming has continued in the south, as has the reduction of precipitation in the south-east. In the north there has been substantial cooling, with its effect on the precipitation/evaporation ratio perhaps allowing us to suppose precipitation has been unchanged. Most of these changes have been felt most strongly in eastern Europe, where the less equable climate is perhaps more easily perturbed.

There is considerable scope for refinement of the reconstructions and interpretations made above. It remains for meteorologists to assess these conclusions and evaluate their plausibility in terms of implied patterns of atmospheric circulation.