PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Climatic Analysis [and Discussion]

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GENERAL DISCUSSION

Climatic analysis

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In opening the proceedings of this meeting Mr J. S. Sawyer of the U.K. Meteorological Office uttered the view that it is really premature as yet to ask a meteorologist to interpret the events of the last glaciation. Nevertheless, that is just what I have been asked to do and, though one must tread warily, I believe it must be attempted. Indeed, it *has* been attempted in a number of scientific papers in recent years and these two days' proceedings have surely helped us to see a number of things more clearly.

I have no time to do justice to all the points that appear interesting.

A meteorologist looks first for the large-scale patterns, which are probably the least difficult to discern and which provide the framework into which all else must fit.

Most meteorologists, oceanographers and perhaps all who are neither geologists nor palaeobotanists, will also probably echo Professor W. A. Watts's reservations about the many names adopted for the various cold and warm stages. One must acknowledge the need which has called the multiplicity of naming systems into being, but the outsider can only accept them reluctantly as marking a provisional stage until the dating is firm and the correspondence of the events known by different names in different parts of the world has been established. This huge, and growing, vocabulary is formidable to those outside the debates about the field evidence and tends to deter other scientists who might contribute to interpreting the processes of climatic change in the Quaternary. From this point of view, and to such audiences, dates and numbered stages, or one single series of names, are much to be preferred.

Data

This meeting has revealed an abundance of data about the last glaciation which would have astounded any previous generation of scientists. With many new types and techniques of observation, measurement and analysis have come global coverage, knowledge of many more fluctuations, and possibilities of corroboration from quite independent lines of evidence. Discrepancies in the apparent climatic indications, where they occur, provide insights into different types of impact and response rates. It seems likely that the most reliable approximation to absolute values of the elements of past climatic regimes will generally come from physical science, particularly from isotope measurements. The records of past ice volume and palaeotemperatures indicated by the oxygen isotope measurements on material from ocean-bed cores (Shackleton's record of the last 2 Ma) and from the Greenland and Antarctic ice sheets, together with the CLIMAP world map of ocean surface temperatures at the last glacial maximum, seen at this meeting, must be accounted triumphs of palaeoclimatic research.

All our data are, nevertheless, only estimates to which some margin of error applies. And that is actually still the case, despite all refinements of instrumentation, with observations of the present régime today – most particularly as regards rainfall over the oceans, snowfall anywhere, sea surface temperatures and temperatures in the upper air. And in all cases, ancient and modern, we must question the representativeness of the observations available on account of the site and time to which they refer.

Causes and mechanisms, amplitude and phasing of the climatic changes

Spectral analysis of such records as we have seen of Pleistocene climatic variations, reported by J. D. Hays, J. Imbrie and N. J. Shackleton at the Norwich symposium on Long-term climatic fluctuations, published by the World Meteorological Organization (*W.M.O. No. 421*, Geneva 1975), seems now to verify the Milankovitch thesis in so far as the timing (if not the amplitude) of the major climatic fluctuations is dominated by the periods of variation of the Earth's orbital characteristics (ellipticity, obliquity and precession), of about 100000, 40000 and 20000 years.

The phasing of the climatic changes in the northern and southern hemispheres needs further study and explanation. The large-scale long-term variations seem to run nearly in phase in both hemispheres; though we have seen evidence that over the last 5000 years – and this is also true of some of the much shorter-term fluctuations – the histories may be out of phase.

It may seem surprising that the British Isles, which today enjoy such an equable climate, cushioned by the surrounding seas from the severer seasonal shocks and year-to-year variability of the continental interior, emerge as one of the regions of greatest change in the ice age–interglacial cycles. To describe this as increased 'continentality' of the climate in glacial times, though literally true, does not tell the whole story: in particular, it overlooks the substantial contribution from the ocean to the variability of our climate.

The amplitude of year-to-year climatic variability as well as the seasonal range within the year varies with time and differs in different régimes. This is registered by the variability of the yearly ring widths in oak-trees in central Germany since A.D. 1280 in figure 1. Four distinct periods of greatly enhanced variations stand out: about 1300, 1550, 1700 and 1860, coinciding respectively with the end of the medieval warmest régime, the beginning and end of the coldest stage of the so-called Little Ice Age climate and the beginning of the century-long retreat of the glaciers in most parts of the world. There can be little doubt that the enhanced variability in those periods was associated with great prevalence of 'blocking', i.e. of stationary wind circulation systems in middle latitudes, occupying somewhat different longitudes in different years (so that any one place experiences sometimes prevalence of northerly, sometimes southerly winds, sometimes persistent anticyclonic weather and droughts, and sometimes a focus of cyclonic activity and repeated rains). It may be that such marked enhancements of the frequency of blocking patterns, replacing the smooth flow of the middle latitudes westerlies, constitute a regular signal of the end of a régime – whether the ensuing change be great or small.

It also seems likely that the year-to-year variability of temperature in the British Isles in glacial times, with the boundary between the persistent snow and ice surface and much warmer land and ocean surfaces near, would be two to three times as great as now, resembling that in Spitsbergen or Archangel today.

The explanation of the magnitude of the longer-term persistent changes of climate in the British Isles may well lie in the variations of the supply of polar water in the East Greenland

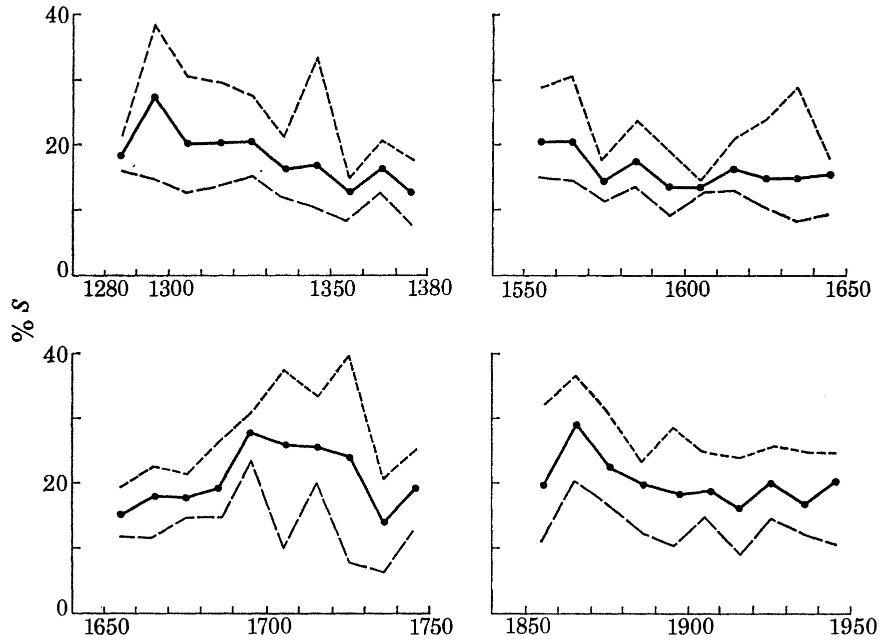

FIGURE 1. Mean variation of ring width from year to year in oak trees in the Spessart forest area, central Germany in various periods since A.D. 1280. ——, average of many trees; ----, extreme values of the period-averages obtained from individual trees. (From Fürst 1963.)

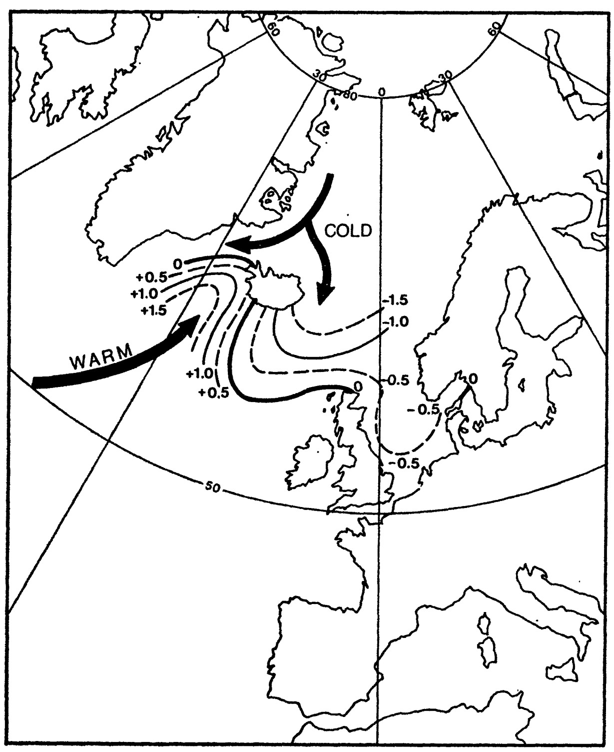

FIGURE 2. Sea surface temperatures measured in the summer of A.D. 1789, during the voyage of the Stanley expedition to the Faeroes, Iceland and Denmark, as departures (°C) from twentieth-century (1919–38) averages. (Data in West 1970.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Current and its extensions, when the flow is strongest, on both sides of Iceland ultimately to 42° N in the eastern Atlantic at the glacial maximum, as demonstrated by Professor McIntyre. Figure 2 provides evidence – from sea surface temperatures measured during one of the relasively warm European summers within the Little Ice Age period – of a more recent thrust of this polar water which changes the character of those parts of the northeast Atlantic that it reaches.

Fishery records from the Faeroe Islands and occasional sightings of extensive drift ice indicate that water surface temperature probably departed by up to −5 °C from modern values in that region for long periods during the Little Ice Age in recent centuries: this would go far to explain the many reports of permanent snow on the tops of the Cairngorm mountains in Scotland between about A.D. 1600 and 1800.

Icelandic oceanographic work over the last 30 years indicates that the water volume transport southwards in the East Greenland Current and northwards in the warm North Atlantic Drift water near Iceland are more or less uncorrelated (S.-A. Malmberg, personal communication): the Arctic Ocean watermass balance must therefore be maintained by the other variables, including atmospheric moisture, river flow and flow through the Bering Strait from the Pacific.

We need an understanding of the mechanisms of climatic change, and the variations of this ocean current may be one of them. Shorter-lived advances brought the polar water near to the Faeroe Islands again in 1888 and 1968.

We also need to study the rapidity, and the course, of climatic changes, recognizing that most available fossil evidence – with margins of uncertainty in the dating and disturbances of the surface of deposits – blurs the changes, extending their apparent period of development and reducing their range.

Atmospheric circulation patterns: various stages of the last glaciation

Reconstructions of the prevailing patterns of the atmospheric circulation and of other aspects of past climatic régimes have so far nearly all concentrated on quasi-stationary situations, which apparently lasted for some thousands of years: long enough, it is hoped, to render errors in dating of the evidence of the pattern unimportant. The circulation patterns so developed are those which represent a continuing response to the same forcing conditions. They therefore tell us nothing about the processes which brought about the change from one régime to another. This applies equally to the world map of ocean surface temperatures at the last glacial maximum which we have seen, to the January and July wind circulation patterns first reconstructed for the same epoch by Lamb & Woodroffe (1970) and to those produced by the most sophisticated general circulation models since. One of the attractions of the latter is that they produce proposed daily positions of individual travelling cyclones and anticyclones – as illustrated by the Williams *et al.* (1974) work in figure 3 – and, in some cases, estimates of precipitation amount etc. But one must ask how successful the same models are in reproducing the known circulation characteristics of the present day. This comparison is provided by Williams *et al.* (1974), and their results for the last glacial maximum are quite similar to Lamb & Woodroffe's. But some other circulation models which indicate more easterly surface winds in middle latitudes produce a great deal too much easterly wind (and too strong monsoonal development) in the present-day régime.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Lamb & Woodroffe (1970) also reconstructed mean circulation maps for the Late Glacial warm substage known as the Allerød Interstadial and for the cold substage (Zone III in the European pollen diagrams) which followed. On the interpretation so derived the surface wind régime was generally easterly over Britain in both substages, but with southerly components in both summer and winter in the warm substage and northerly components in the cold substage: this change resulted from a westward shift ('retrogression') of the controlling features of the atmospheric circulation over Europe, as the thermal gradients and circulation strength gradually weakened in middle latitudes over the Atlantic and Europe, implying shortening wavelength in the upper westerlies. This result, however, seems – at least at first sight – to conflict with the

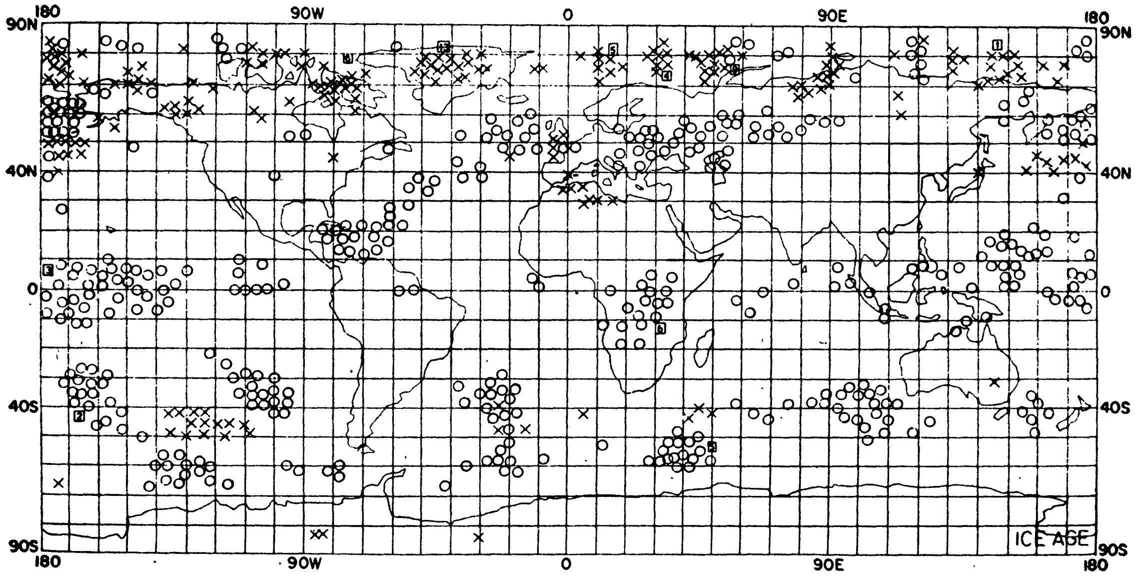

FIGURE 3. Positions of cyclone and anticyclone centres on days 51–80 of integrations with the NCAR globa circulation model: July ice-age situation. (From Williams *et al.* 1974.)

evidence reported by Manley (1959) that the winds which produced the reappearance of corrie glaciers in the Lake District of northwest England were southwesterly. Can it be that the climatic change between the warm and cold substages was brought about quite quickly by an interval in which southwesterly winds prevailed with slow-moving cyclonic centres nearly over the British Isles (probably in the Rockall–Hebrides region) and repeated outbreaks of arctic air and a cold ocean current from the north over the Atlantic just west of these islands?

I believe Professor G. F. Mitchell has put an important proposition before this meeting in his suggested 'frost cycle', distinguishing an onset phase in which abundant snowfall occurs with temperatures not nearly so low as subsequently develop. The winds prevailing in the ensuing cold stage may be quite different from those under which the glaciers and ice sheets formed.

Similarly the variations of strength of the upper westerly winds over Japan, derived by Yoshino & Tabuchi (1975) from survey of the volcanic ash deposits from the ever-active volcanoes, has indicated a phasing in which the westerlies were strongest at times of increasing glaciation in the northern hemisphere and much weaker at the maxima of glaciation.

The proposed circulation pattern of the glacial onset in the early Devensian/Weichselian/Wisconsin (figure 4), put forward by Lamb & Woodroffe (1970), illustrates the results of similar thinking and would fit the circumstances of the change from Late Glacial Zone II to Zone III proposed above if the features of the circulation over Europe were displaced about 20° of longitude to the west. Such a displacement could very well have occurred at some stages in the Early Glacial also. Both positions would be consistent with massive enhancement of the East Greenland Current and its extension in branches east of Iceland and south of Denmark Strait – the

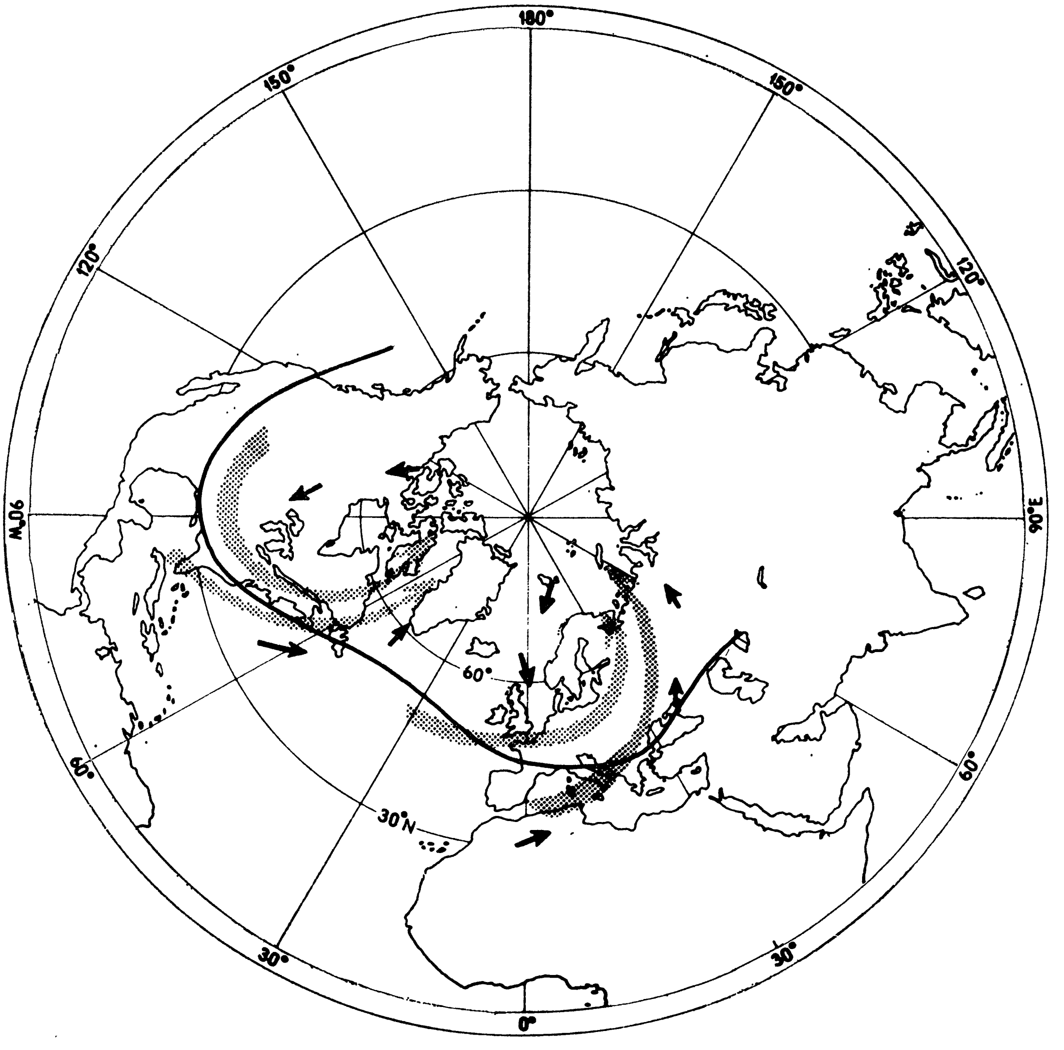

FIGURE 4. Proposed atmospheric circulation pattern prevailing during onset of the last glaciation (Lamb & Woodroffe 1970). ——, 5300 m height contour of the 500 mbar surface in January; ➔, prevailing surface winds; long grey arrows, main tracks of surface-level cyclone centres.

McIntyre–Ruddiman glacial current – carrying the polar water farther south. Even the more modest climatic fluctuations of recent times – the Little Ice Age development and the cold years in the 1880s and 1960s – seem to show a similar pattern, only less extremely developed and of briefer duration. The great postglacial warming and the notable warming of northern climates in the early twentieth century both entailed an equally great predominance of southerly surface wind components and northward thrust of the warm North Atlantic Drift water over the eastern Atlantic, through Denmark Strait and the entire Norwegian Sea.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

MID-DEVENSIAN/MID-WEICHSELIAN CLIMATES

This meeting has also produced, in the paper by Professor R. G. West, a notable mustering of data from a network of points over Europe on the nature of the mid-Devensian/mid-Weichselian climates, which for tens of thousands of years were neither fully glacial nor fully interglacial. Dr Coope and others at Birmingham have over the years contributed greatly to our

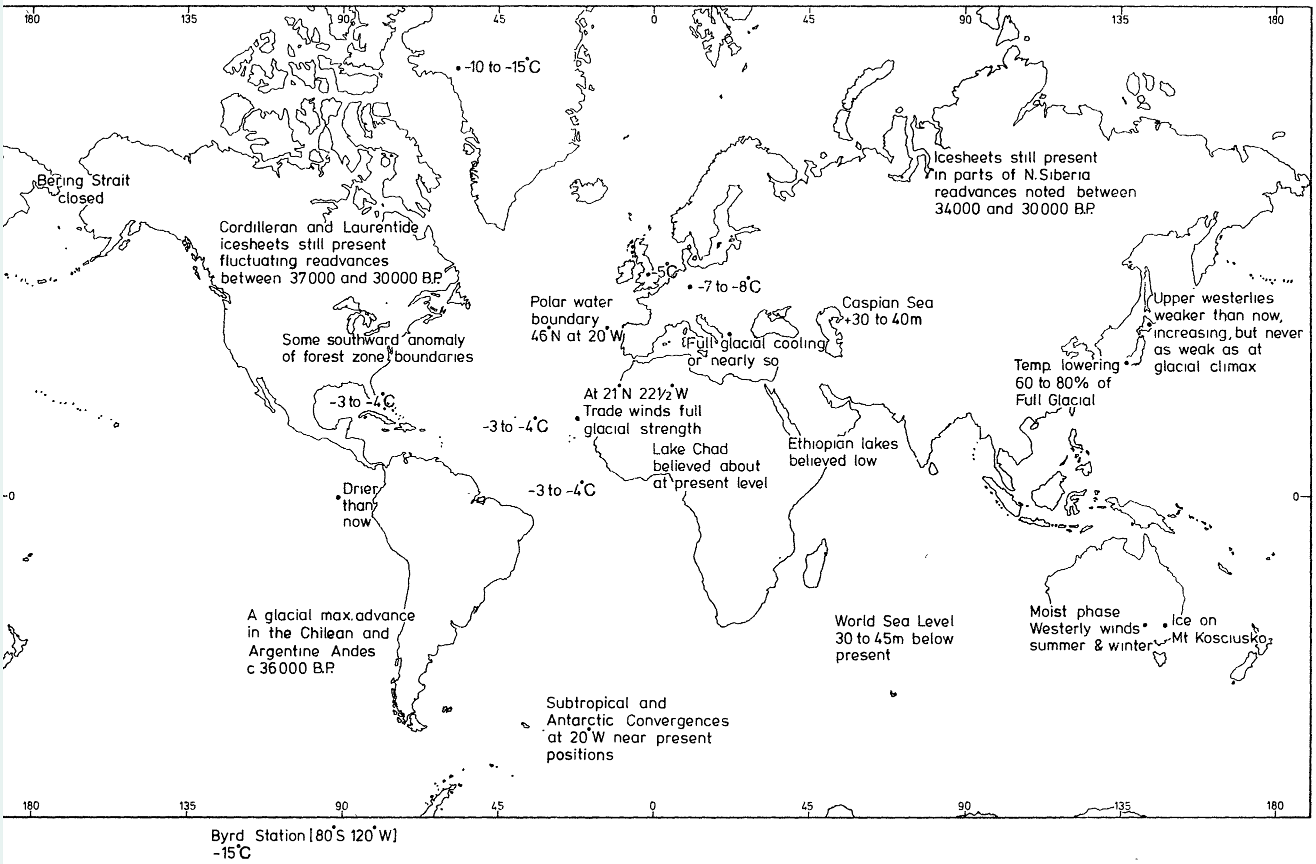

FIGURE 5. Summary of present knowledge about mid-Weichselian/mid-Wisconsin climate from 40000 to about 25000 years ago. Unlabelled temperatures are departures (°C) from modern averages. Dots mark positions to which the observations refer.

knowledge of the detailed succession over the British Isles, and Dreimanis & Raukas (1975) have lately attempted a hemispheric survey. As a result we are now approaching the possibility of a meteorological interpretation of this very strange climatic problem.

The kernel of the problem seems to be: why did the solar radiation budget, which according to the Milankovitch orbital considerations was particularly around 45000–40000 years ago very similar to what it is today, fail to produce a climate and environment similar to today's?

Figure 5 gives a global survey of conditions during the long period of what may perhaps be described as cold-temperate climates between about 40000 and 25000 a B.P. They may be summarized as intermediate between present and glacial conditions, though very much nearer to full glacial than to the present régime. They had been briefly preceded, apparently about 43000 B.P. in the British Isles, by a régime indicated by the beetle evidence as having warmer summers than now, though with no development of the temperate forest landscape. This was related to the times of maxima of northern-summer radiation receipt in low and high latitudes 5000–15000 a earlier similarly to our position today, except that the summer radiation maxima that time were less strong and the winters produced a deficit by comparison with the millennia leading up to our own times. Thus the integrated total radiation available over the preceding millennia was significantly less than now. To that can surely be attributed the failure of the northern continental ice sheets to melt completely away. Sea level remained low, and the Bering Strait remained effectively closed even at the warmest stages of mid-Weichselian times.

According to Professor A. McIntyre's studies, the area dominated by polar water in the eastern Atlantic shrank back just to Iceland. Correspondingly, the Scandinavian ice sheet withdrew probably to about 64° N in central Sweden at the warmest phase, though in eastern central Europe the forest (including warmth-loving trees) seems to have spread north to Estonia beside the Gulf of Riga. Can it be that the failure to open a through channel from the Arctic to the Pacific was crucial? Although the flow of water through the Bering Strait, from the Pacific into the Arctic, at the present day amounts to only about one-tenth of the watermass budget of the Arctic Ocean, there is some evidence that that flow varied significantly during the Little Ice Age fluctuation. Can it be that it was necessary for that channel to be open to a reverse flow before the Atlantic warm water could begin to penetrate all the Arctic Ocean regions beyond Iceland?

The pattern described suggests a thermal gradient which would produce prevalence of southerly winds over Europe in the summers of all those millennia when the continent was warm and the polar water and largely ice-covered sea lay close to the western seaboard. The summers could then be very warm in the continental interior, though the winters would be cold. The one millennium in which the polar water retreated to 64° N may have produced prevalence of southwesterly winds, particularly over the southern half of Europe, and Coope may well be right in describing its climate as oceanic in these islands.

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Discussion

H. T. Mörth (*Climatic Research Unit, University of East Anglia, Norwich NR4 7TJ*)

As a climatologist, I should like to put the following issue to the biologists, especially the botanists. Future explanations of the state of the atmosphere during periods of glaciation may well include major changes in the temperatures and circulations of the stratosphere. Major variations in the amounts and distribution of ozone could be inferred. Since ozone filters out the ultraviolet portion of the solar radiation spectrum, this would imply variations in the amount of ultraviolet radiation received at the Earth's surface. Temporal changes in the plant and animal distribution during the Devensian that were put forward by a number of speakers during this meeting were attributed to temperature variations. Is there any evidence for differentiation according to the need for, or tolerance of, certain levels of u.v. radiation?

A. Dreimanis (*Geology Department, The University of Western Ontario, London, Canada*)

Several of the papers presented during this two-day meeting demonstrated that the Devensian stage experienced a wide range of climatic and environmental changes both in time, and laterally from one area to another, during any particular time interval. This was clearly demonstrated by the CLIMAP palaeoclimatic maps for the Late Devensian maximum and its correlatives 18000 a B.P.

Similar variability, though from a more spotty record, was suggested for the Middle Devensian and its correlatives in Europe: grasslands dominated in Ireland and Britain, possibly due to the cooling effect of the Atlantic Ocean, in spite of the brief very warm episode 43000 a ago. About the same time, forest tundra and forests spread into some parts of the continental Europe and northern Asia, even to higher latitudes than Britain, probably because of sunny warm summers and the dominance of high barometric pressure over the continental interior. The environmental differences between the near-Atlantic area and the interior of Eurasia have been so contrasting during the Middle Devensian and its equivalents, that these intervals have been called interstadials, interstadial complexes, or pleniglacial in the west, but considered to be interglacials, e.g. Karuküla and Karginsk, by some authors in the east.

If the above model of general west–east differences in Eurasia is correct, then even more contrasting mirror-like east–west climatic and environmental differences should be expected on the other side of the Atlantic – in the middle latitudes of North America. Why more contrasting? Because, according to the CLIMAP maps of the Atlantic Ocean, the polar front remained farther south along the eastern Atlantic coast of North America, than its eastern counterpart along the western coast of Europe. About ten days ago, on 19 and 20 March, regional east–west correlations for the last or Wisconsin Glaciation were discussed in Ottawa by the Canadian group of the IGCP Project 73/1/24 on Quaternary glaciations in the northern hemisphere. These correlations suggested the following east–west environmental and climatic change in southern Canada during the Middle Wisconsin substage: (*a*) the Appalachian glacial complex and the Laurentide ice sheet still covered most of the Atlantic Provinces of Canada (except for the coastal areas), and the St Lawrence Lowlands, at latitudes of southern Europe; (*b*) cool boreal climate and open woodlands were present in the Great Lakes Region at the same latitudes; (*c*) a climate little cooler than at present existed in south-central Manitoba, considerably northwest of Great Lakes, at the latitude of southern Ireland and southern Britain; (*d*) the summers were dry and as warm as at present or even warmer in the Peace River area of northwestern Alberta – at the latitude of north-central Labrador and Scotland. Another opposite climatic mirror image developed along an east–west traverse towards the Pacific: dry warm summers and complete deglaciation in south-central British Columbia, but a cooler interstadial climate, as concluded from pollen records, near the Canadian–United States border along the Pacific. As the duration of Middle Weichselian or its correlatives was several tens of thousands of years, the climate changed during this long interval in each of the areas mentioned; therefore the warmest episodes, which occurred before 40000 a B.P., were chosen for the above comparison.

H. H. LAMB. I hope that these suggestions and comments may indicate some profitable lines for further research. And I should like to congratulate those who organized this meeting, and the contributors, on the outcome. The research reviewed in these two days and the ideas and interpretations spoken of surely mark a great advance in our understanding of the development of the environment and of the parts played by the atmosphere and oceans in that development.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES