PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Climate, Vegetation and Forest Limits in Early Civilized Times

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Climate, vegetation and forest limits in early civilized times

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CONTENTS

After reviewing the basic conditions which govern climate and the distribution of climates over the globe, with particular attention to the large-scale circulation of the atmosphere and the variations which it undergoes, this contribution proceeds to consider the sites of the early centres of civilization (particularly those that flourished between about 3000 and 1000 B.C.) and routes of travel by land and sea, some of which stand in a surprising relationship to the natural environment as it exists today. The sequences of variations of prevailing temperature, of sea level, of forest limits and rainfall, cloudiness, etc., and of the levels of great inland waters are reconstructed and lead to a consistent picture of the broad sequence of climatic régimes: for those régimes which differed most from the present-day northern hemisphere maps can be given. Climatic fluctuations on time scales from a decade or two to a few centuries are then considered: fluctuations tending to repeat at 200 or 400-year intervals seem rather prominent.

Introduction

Weather and climate are forever changing. Sometimes the changes are sharp, sometimes gradual. The spectrum of time-scales involved runs from minutes to millions of years. Not only does one year's experience differ from another in a middle latitudes climate such as Britain's: there are differences also in the Sahara desert, in the islands of the equatorial Pacific and in the heart of the polar regions. Moreover, the climatic experience of each decade, each century, each millennium in any one part of the world differs.

There has been some confusion about this. Many kinds of physical as well as biological evidence (see, for example, Ahlmann 1949, Dansgaard, Johnsen, Clausen & Langway 1971; Imbrie & Kipp 1971; Turekian 1971) now contribute to our reconstructions of the past climatic record. Yet many people who are not well acquainted with the multifarious nature of the evidence still hold to the view that there have been no significant changes of climate since the end of the last ice age some 10000 years ago (see, for example, Raikes 1967). It is true that Tacitus's writings about the climates of Britain and Germany, and Herodotus's description of the Crimea, register the same impressions that would strike visitors from Italy and Greece today; but this need mean no more than that the spatial differences were in the same sense then as now. Moreover, much evidence suggests that about 2000 years ago the climate in many countries was passing through a phase quite similar to today's. Some centuries earlier there had been a colder régime (as is also true today). It subsequently became milder, and the bridge of many stone piers with a wooden superstructure built for the Emperor Trajan in A.D. 106 across the Danube at the Iron Gates stood for about 170 years (before being destroyed by the barbarian tribes) in a position where today it might be expected to be carried away by ice within any period of 50 years or less.

Archaeologists, botanists, and some meteorologists, have been sometimes suspected of calling in entirely hypothetical climatic changes, as a sort of *deus ex machina*, to explain shifts of vegetation limits which might more properly be ascribed to the works of Man, clearing and burning forests, grazing with goats, building and later neglecting irrigation works, and so on. But, since Roman times, the occurrence of a period in the early Middle Ages that was moister than now in the Mediterranean is well attested by bridges (e.g. at Palermo, Sicily) built to span rivers that were bigger than now, and by widespread evidence of more active stream erosion and deposition. The warmth of the same medieval period in higher latitudes is registered in the absence of ice on the Viking sailing routes to Greenland, particularly in the years between about A.D. 980 and 1200, and by the increase of ice which followed there and in the glaciers in the Alps. There was a lowering of the upper tree line on the mountains in central Europe by 200 m between about A.D. 1300 and 1600 (Firbas & Losert 1949) and a parallel change in the upper limit of trees in the United States Rockies (Lamarche 1972). Within the last few years, the ascription of these changes to changes of prevailing temperature has been effectively verified by oxygen isotope measurements on the ice of the times concerned, still present in the Greenland ice cap (Johnsen *et al.* 1970; Dansgaard *et al.* 1971). Moreover, significant shifts of the northern (and, in some cases, also the southern) limits of various species of birds and fish, of forest trees and wild flowers, in response to the general climatic warming in the early decades of the present century and to the cooling since about 1950, have been widely observed and reported (e.g. in Perring & Walters 1962; Perring 1965).

The natural limits of different types of vegetation – and of the faunas whose habitats the vegetation provides – are thus seen to undergo shifts from century to century and sometimes over shorter periods. The species composition of the vegetation had undergone some changes in response to earlier, and in some cases harsher, changes of climate than those so far mentioned. Therewith, the possibilities of agriculture and husbandry must have changed, particularly in areas near the thermal or arid limits of particular crops and grasslands. Human society, especially primitive human society, and economies based on a narrow range of resources, must have had great difficulty in adapting to some of the changes, and in a number of cases migration may have been the only solution. This suggestion, first put forward by Huntington (1907) in relation to drying up of the pastures in the homelands of the nomads of central Asia around A.D. 300 and the *Völkerwanderungen* of the time of the demise of the Roman empire, looks sensible in the light of the rainfall changes in central Asia in the last 130 years (figure 1) (cf. also Chappell 1970). Sixty years between 1890 and 1950 of a climatic régime in Khazakstan moist enough for grain cultivation were followed in the 1950s and later 1960s by a lower rainfall, as in the mid-nineteenth century, only one-half to three-quarters as great.

The climatic connexion of some important environmental changes is obscured by lag in the response. When a warming up of climates opens up the possibility of forest spreading poleward,

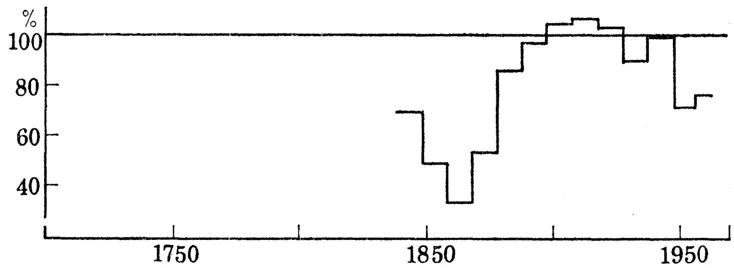


FIGURE 1. Rainfall averages for successive decades between 1840 and 1960 at Barnaul (53° N, 84° E), representing the grasslands of central Asia. Units: per cent of the 1900 to 1939 yearly average rainfall (482 mm).

much time may be required before all the new areas are colonized because of the limited spread of seed and the shelter needed for young trees to survive, needed also by the birds and insect life which help to spread the seed. And, after a turn to more arid climates in the fringes of the desert zone, the old forests may be able to survive for hundreds, and even thousands of years, thanks to the local preservation of soil moisture in the shade and moisture exchanges within the forest itself. But forests in this situation are 'sub-fossil', precarious relics of a past climatic régime: once they have been felled, or burnt, or encroached upon by grazing animals, the change is likely to be irreversible.

Basic conditions of climate

The climate of any place is produced by:

(i) *The radiation balance* there, the incoming radiation being graduated according to solar elevation and length of day, i.e. latitude and season.

(ii) *The heat and moisture brought and carried away by the winds and ocean currents.*

(iii) The *local conditions of aspect* towards the midday sun and the prevailing winds, *thermal characteristics* (specific heat and thermal conductivity) *of the soil and vegetation cover*, also the *albedo* (reflectivity) of the surface and hence the amount of radiation actually absorbed.

The local thermal characteristics are most of all affected by:

(*a*) *Wetness or dryness of the surface*, dry ground being subject to much the quicker temperature changes (owing to its low specific heat and poorer thermal conductivity below the surface).

(*b*) *Snow-cover* or the lack of it, since the high albedo of a snow surface means that most of the solar radiation falling on it is reflected and lost; the snow surface, moreover, radiates away heat to the sky and to space; and because of the air trapped within a snow layer its conductivity is poor and the temperature fall is concentrated near the surface.

The global climatic pattern is at all times generated by the radiation distribution and the general circulation of the atmosphere and oceans. This large-scale circulation of the winds, and the ocean currents which they drive, is set up by the unequal heating of different latitudes. Vertical expansion of the air columns over the heated zones of the Earth, and contraction of the air columns in high latitudes where most heat is lost, determines a rather simple global distribution of pressure through a great depth of the atmosphere between about 2 km and 15 to 20 km above the Earth's surface: high pressure generally over the warmest zones in low latitudes and low pressure near the poles. This pressure distribution, over the rotating Earth, maintains a rather simple pattern of wind flow, of prevailing upper westerly winds, throughout the same deep layer of the atmosphere: i.e. a circumpolar vortex over each hemisphere.

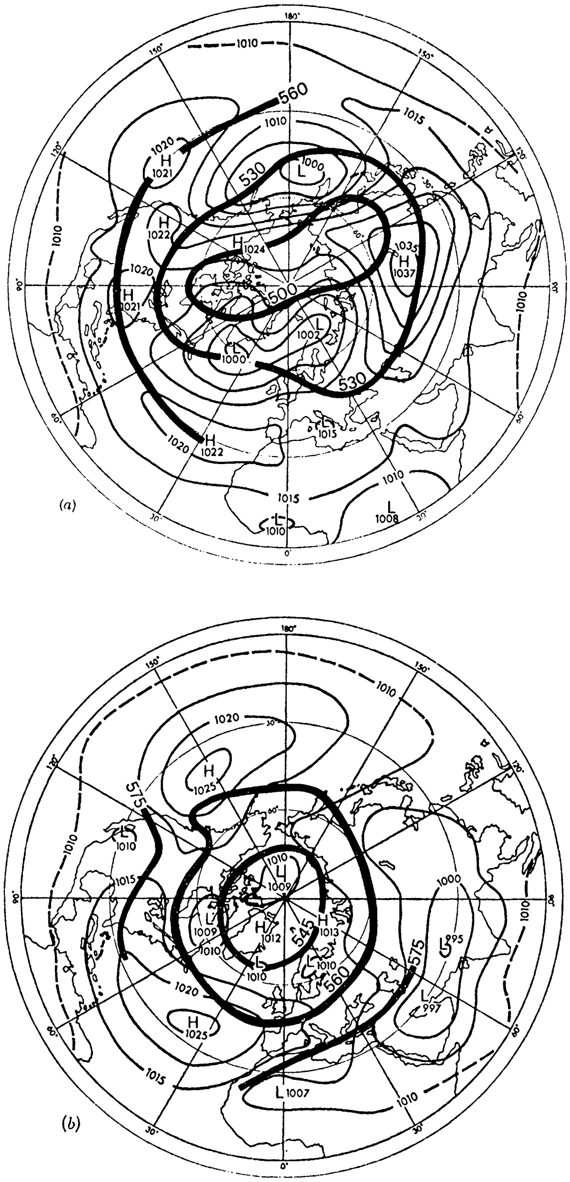


FIGURE 2. (*a*) Average atmospheric pressure over the northern hemisphere at sea level (in millibars) in January in the 1950s and (bold lines) thickness (in decametres) of the lower half of the atmosphere (1000 to 500 mbar layer), the latter to indicate the upper westerly wind flow. Winds at both levels blow (except where diverted by surface friction) nearly along the isopleths counterclockwise around the low-pressure regions (clockwise in the southern hemisphere). (*b*) Average atmospheric pressure and thickness in July, 1950s.

There are waves in the upper westerlies, as the flow meanders round the barriers of the Rocky Mountains, Greenland, and the mountains of Asia and is influenced by the warmth of the northeast Pacific and the Atlantic–Norwegian Sea as well as by the persistent cold surfaces of Arctic Canada and icy waters elsewhere, particularly in the tundra zone in northern Siberia and the Okhotsk Sea. The strongest thermal gradients and the strongest upper wind flow are in general in middle latitudes, though constrained here and there (and more at some times and seasons than others) by the geography, as mentioned. The wave train in the upper westerlies also develops its own dynamics, so that there is a tendency for a trough in the flow somewhere near the European sector as a resonance effect downstream from the trough maintained in the lee of the Rockies and over the cold surface of northern Canada. This downstream trough itself tends to induce a régime that is cold for its latitude wherever it lies at any given time over northwest Siberia, Europe or the eastern Atlantic. The longitude position of the resonance trough depends on the preferred wavelength in the upper westerlies, which increases with the latitude and strength of the mainstream of the upper wind flow.

The relationship between the circumpolar vortex of upper westerly winds and the more complex, but more familiar, distribution of high and low pressure on the surface weather map is intimate. It is this which makes it possible to derive much of the hemispheric climatic pattern from fragmentary surface data. It is illustrated here by the average situations in January and July in the 1950s seen in figure 2*a* and *b*. Convergences and divergences in the upper flow (at points where the pressure gradient changes) continually generate accumulations and losses of atmospheric mass over the areas affected, and the resulting surface-level pressure systems and wind circulations are steered and carried along by the general pattern of the upper westerlies. Surface low-pressure (cyclonic) systems are generated mostly at the forward (i.e. eastern) side of the troughs in the upper flow and are carried along, and towards, the cold flank of the mainstream of the upper westerlies. Surface high-pressure (anticyclonic) systems are generated mostly in the converse positions, at the rear of the upper troughs and are steered along, and towards, the warm flank of the upper flow.

These associations produce the following *prevailing distribution of atmospheric pressure at the Earth's surface:*

(*a*) A subtropical high-pressure (anticyclonic) belt along the warm side of the mainstream of the upper westerlies, developing the clear skies of the desert zone.

(*b*) A subpolar low-pressure belt, the locus of the centres of the main depressions, or travelling cyclones, associated with belts of cloud and rain (or snow) continually sweeping forward in the zone of prevailing westerly winds and near the cyclone centres.

The distribution also leaves room for:

(*c*) Higher pressure near the pole.

(*d*) An equatorial low-pressure trough where the surface Trade Winds from the two hemispheres converge.

The *prevailing surface wind zones* defined by this pressure distribution are

(i) Easterly (in the northern hemisphere mainly northeasterly) Trade Winds, between the subtropical high-pressure maximum and the equatorial low-pressure trough.

(ii) Westerly (in the northern hemisphere mainly southwesterly) surface winds in middle latitudes.

(iii) Polar easterly surface winds, prevailing between the latitude of the subpolar depression centres and the polar high-pressure maximum.

This outline of general principles (for further elucidation see Lamb (1972) and refs. therein) is essential to an understanding of variations in the pattern which occur from time to time, including those tendencies which seem to have prevailed in different eras in the past.

The types of variation to which the circumpolar vortex is liable may be listed as follows:

(1) Changes of strength of the upper westerly windstream.

(2) Changes of latitude of the main flow.

(3) Changes of wavelength (or spacing between the troughs) downstream from the nearly fixed disturbances at the main mountain barriers: hence also changes of the trough positions and of the total number of waves around the hemisphere.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(4) Changes of amplitude of the waves, i.e. of the north–south range, or meridionality, of the flow.

(5) Eccentricity: the main centre of the circumpolar vortex may move quite far from the geographical pole, occasionally to latitude 60–70°, though in such extreme cases the situation usually tends to become bipolar (or even tripolar).

The surface pressure and wind patterns become displaced and distorted in sympathy with these variations.

A common variant type of situation is known as *Blocking of the westerlies*, with an anticyclone developing (in association with a meridionally extended warm ridge aloft) in the usual zone of subpolar depressions, and low pressure in the subtropical zone, usually near the entrance to a confluent trough in the upper westerlies (which may become considerably distorted). This is the most abnormal-looking situation in that it produces easterly winds in middle latitudes and twin belts of westerlies near the Arctic circle and in subtropical latitudes, while the Trade Winds are liable to be disrupted. But blocking seldom lasts more than a few days to a few weeks without the pressure systems concerned undergoing a considerable change of longitude. Hence, periods of frequent blocking are represented in the climatic mean mainly by weaker than normal middle latitudes westerlies and weakness of the Trade winds.

The influences that affect the amount of rain falling at a given place in different epochs may be listed as:

(i) The prevailing temperatures of the water surfaces (chiefly the ocean) from which the air's moisture supply is drawn, the absolute humidity of the air increasing with the water temperature.

(ii) The positions of the mainstream of the upper westerlies: (*a*) latitude; (*b*) longitudes of troughs and ridges; (*c*) distorted, 'meridional' and 'blocking' patterns; and hence the locations of frequent cyclone formation and the paths along which these systems are steered, the rainfall increasing with the cyclonicity.

(iii) The most frequent surface wind directions and their aspect to the slopes of the terrain, the rainfall being greatest with upslope winds.

The climatic shift that took place in the early 1960s, portrayed in figure 3 by its effects on the world rainfall distribution, illustrates types of displacement which, in the light of the foregoing principles, may be looked for in other climatic régimes. The shaded areas on the map mark regions where the rainfall from mid-1961 to mid-1964 was above the previous 30-year (1931–60) average; elsewhere it was below the previous average – save that rainfall over the oceans beyond the range of the island observations used could not be surveyed. This map shows the years 1961–4 as characterized by

(i) Increased rainfall in most parts of the equatorial zone.

(ii) Reduced rainfall rather generally in zones on either side of the equator, especially between latitudes about 15 and 25° (presumably indicating less seasonal intrusion of the equatorial rains into these zones).

(iii) Increased rainfall in subtropical latitudes, especially about 40° (more winter rainfall, encroachment of the travelling disturbances of middle latitudes in both hemispheres and frequent blocking with low pressure in the subtropical zone).

(iv) In middle latitudes alternate north–south ('meridional') stripes of excess and deficient rainfall, associated with changed wavelength (and changes in the most frequent trough positions) in the upper westerlies.

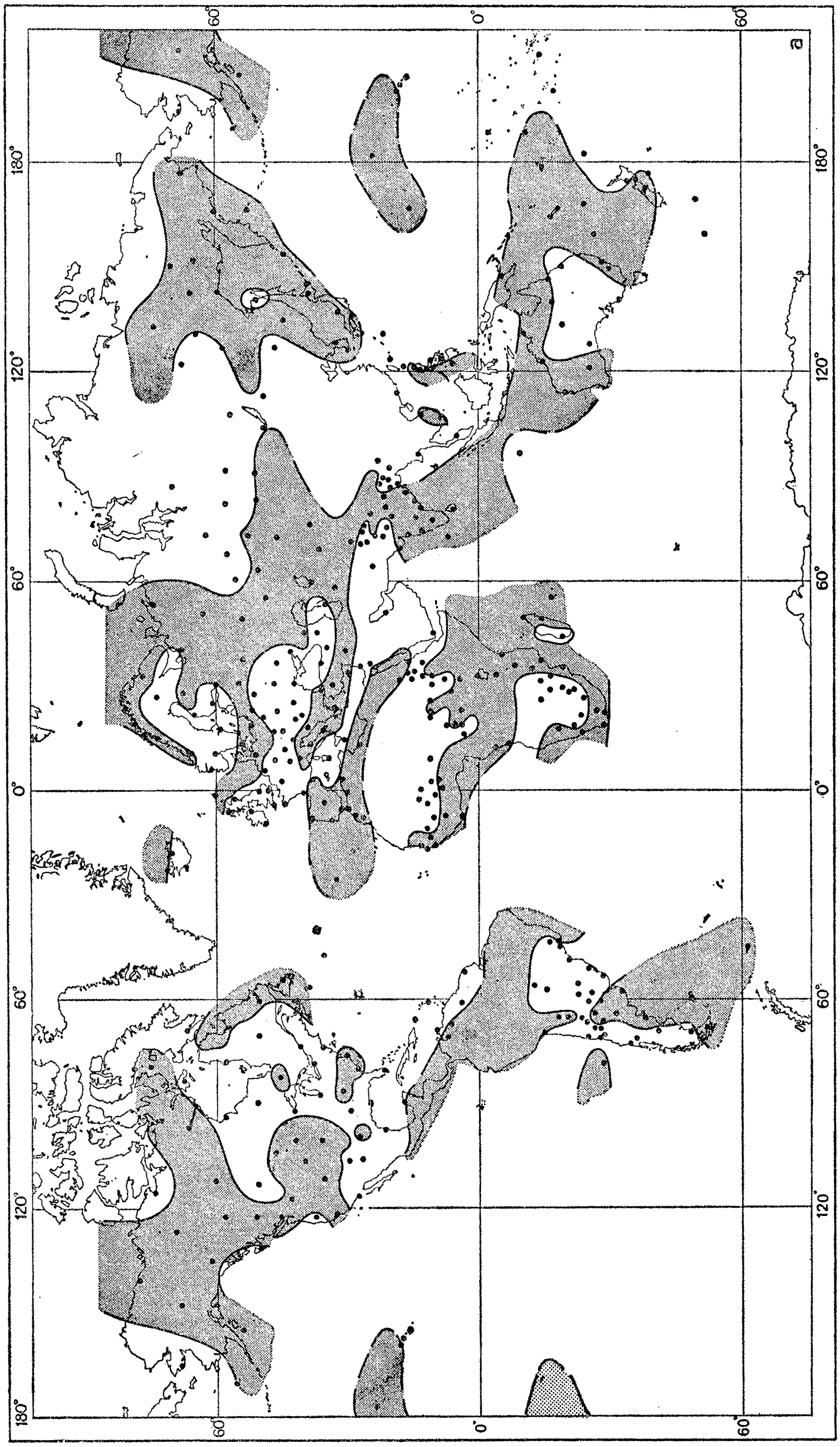


FIGURE 3. World rainfall July 1961 to June 1964: departures from the 1931 to 1960 averages. Dots show stations with complete data used. Ocean areas generally not included in the survey except where the indications from island observations were adequate. Stippled areas: rainfall exceeded 1931 to 1960 averages.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

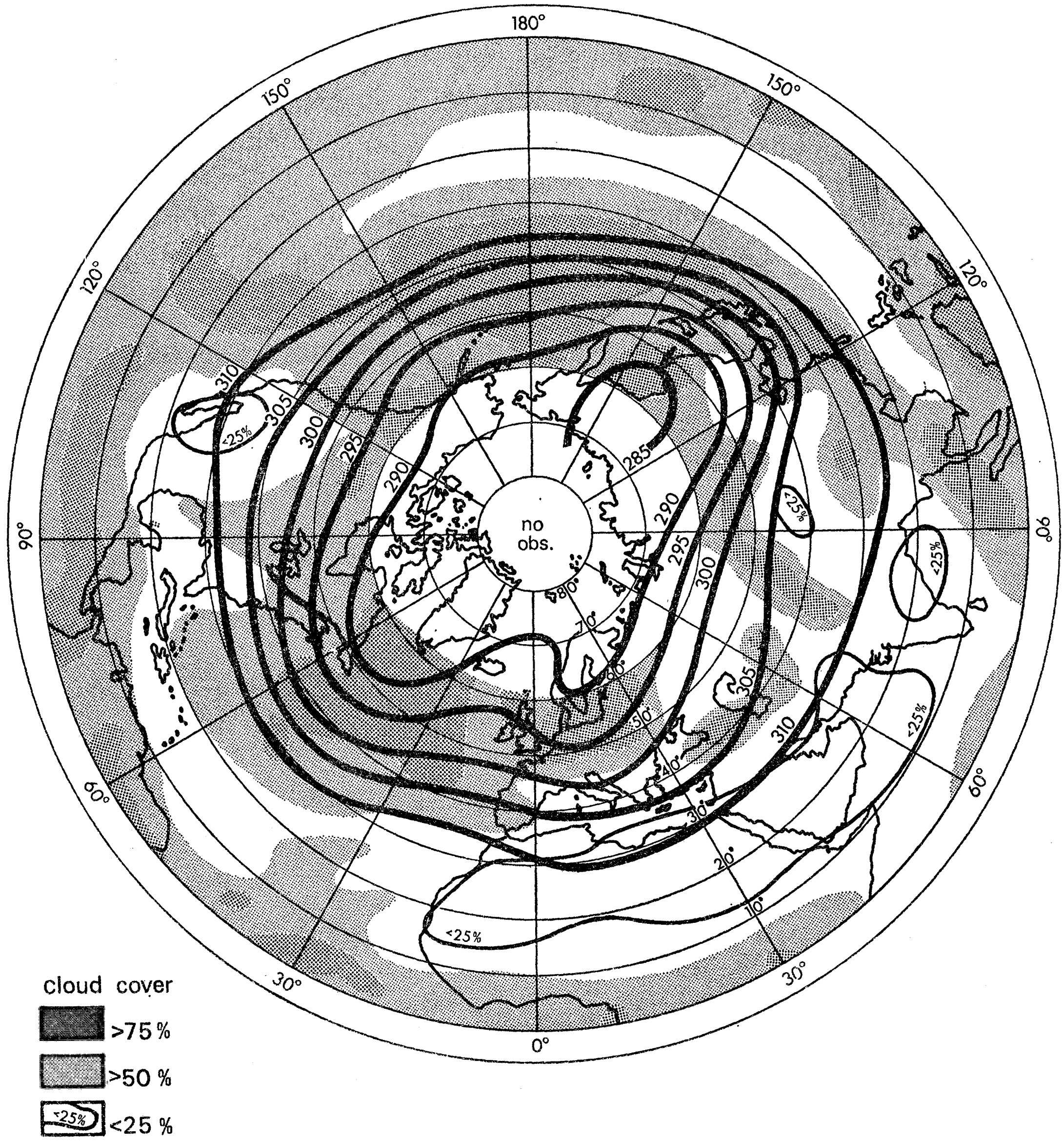


FIGURE 4. Mean cloud cover over the northern hemisphere south of 60° N in spring (March, April and May) 1962 from *Tiros* satellite data (Clapp 1964) and average 700 mbar heights in decametres during the same months.

Converse shifts are known to have occurred about the beginning of the present century.

Cloudiness (other than fogs over cold surfaces and cloud caused by uplift of the wind against the windward slopes of mountain ranges), and *rainfall*, are related to the forward (eastern) sides of the troughs in the upper westerlies, and are carried along in the strong windstream, in the same general way as cyclonic development. This is illustrated here in figure 4 by the first published 3-month survey by satellite photographs of global cloud cover, in the spring of 1962, together with the isopleths of height of the 700 mbar pressure level to show the flow of the upper westerlies at about 3 km height.

The sites of the early civilizations

Figure 5 is a world map of the beginnings of civilization. The areas of origin of the group of civilizations that flourished between 4000 B.C. and the time of Christ are, except in the special case of Egypt and the lower Nile, areas of rather intricate geography, within which the sites then occupied range today from the natural domain of woodland to steppe or desert. The changes in the environment that have taken place there could hardly be shown on a world map and have hardly been probed so closely that valid regional maps of the former vegetation could yet be drawn.

In at least three regions, however, there are unmistakable indications of formerly more extensive water supply and vegetation:

(i) The western and central Sahara, where rock drawings of a wide range of animals (Butzer 1958), and finds of skeletons, including elephants (Monod 1963), show that there was enough surface water for animals to pass across the terrain that is now desert and for at least some human occupation.

(ii) The Rajasthan (Thar) desert areas of India and Pakistan, where rivers have disappeared (Singh 1971) since the Indus valley civilization and the cities of Mohenjodaro and Harappa (31° N, 72½° E) were at their height before 2000 B.C.; also the other desert areas in southern Asia crossed by Alexander's army on expeditions in Iran and on the march to the Indus between 330 and 323 B.C. (On their return, the Indus was crossed in a flotilla built of timber from the local forests (Wadia 1960).) The fauna of the present Thar desert in Harappan times included rhinoceros, water-buffalo and elephant.

(iii) Sinkiang, particularly the Tarim basin in central Asia near 36–42° N, 80–90° E, was crossed by the ancient Silk Route which was used by trading caravans between China and the west in Roman times, when there was a chain of cities and settlements there and remnants of forest. Today it is largely a sandy desert (Wadia 1960; Chappell 1970, 1971).

Other places, where conquest of the area by desert conditions within the last 2000 years suggests a continued trend towards natural desiccation, include Palmyra (34° 40′ N, 38° 0′ E) and Petra (30° 20′ N, 35° 18′ E), on the fringe of Palestine and the Syrian desert, and parts of the Anatolian plateau in central Turkey (Carpenter 1966). It is unlikely that rainfall has been continuously decreasing for thousands of years, but probable that it has been fluctuating with a net downward trend; we shall see evidence of such a trend affecting wide areas of the subtropical zone over the last few thousand years. The vegetation may, therefore, long have been in a subfossil condition, in which disturbance by Man might easily bring on its final demise. Radiocarbon ages of 20000 to 25000 years since last contact with the atmosphere found in the water in a Saharan oasis, and in water-bearing strata under the Sinai and Negev deserts (see, for example, Valéry 1972), make it clear that the water-table in the arid zone in the Near East is still influenced by the supply of rain which fell in previous climatic régimes, particularly those of the last ice age. Certainly, the extent of the oases has been declining over the last 6000 years (Butzer 1958).

A curious feature of figure 5 is the spread of groups building stone circles as early as about 2000 B.C., and trading, evidently by a sea route through the western parts of the British Isles as far north as Orkney (59° N). This may suggest not only some skill in navigation, but an era of rather frequent quiet seas. In apparent support of this suggestion, there is now much evidence from radiocarbon dated pine stumps in the peat (H. H. Birks 1972, personal communication

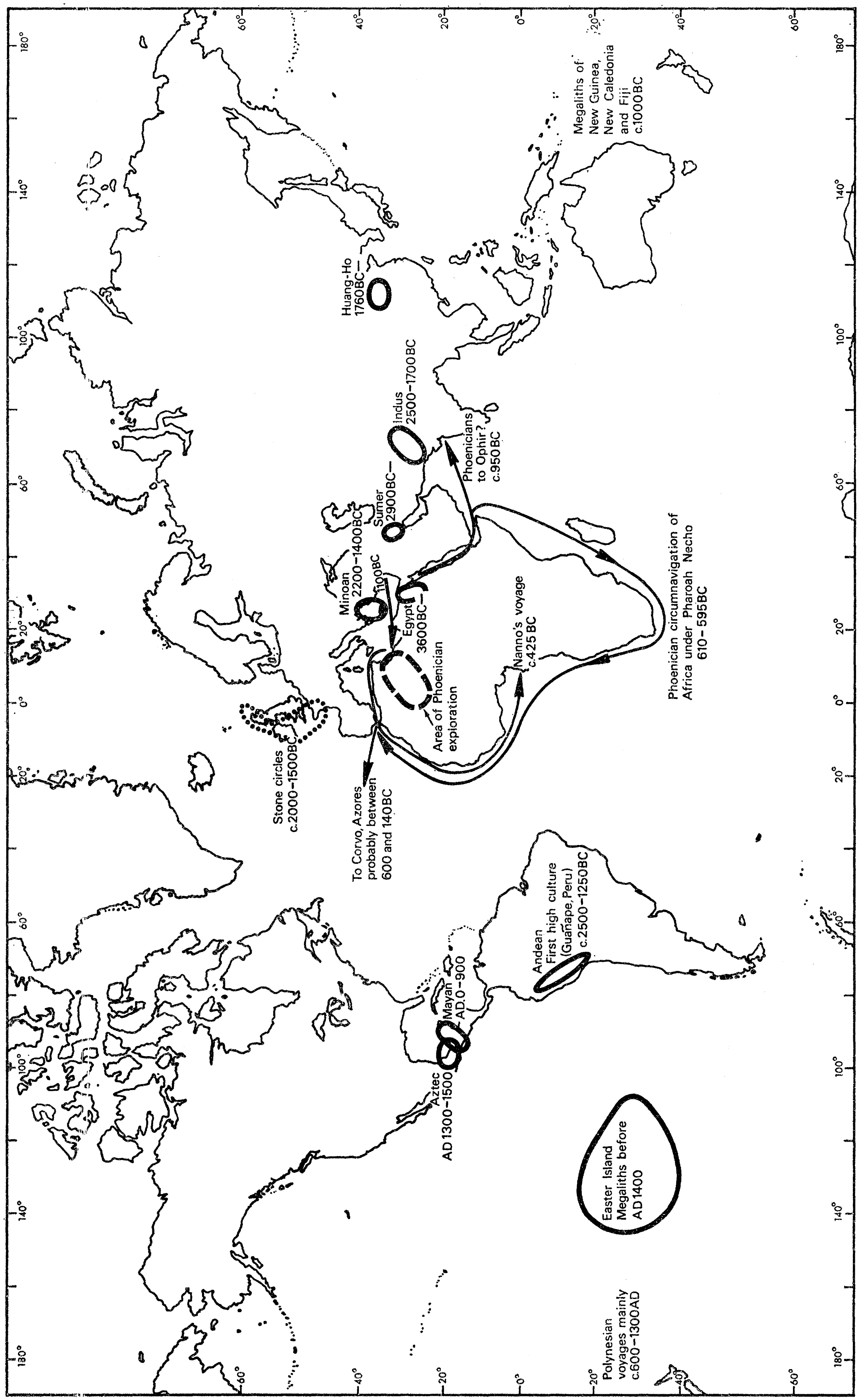


FIGURE 5. World map of the beginnings of civilization.

5 July 1972; Lamb 1964, 1965*a*; Pennington, Haworth, Bonny & Lishman 1972) that between about 5000 and 2000 B.C., forest grew much nearer to the open Atlantic coast of northwest Scotland than at any time since and also in parts of the Hebrides and northern isles.

Setting in the sequence of climate and vegetation history

The ancient civilizations grew up and decayed in times when a previous extensive glaciation of the northern hemisphere was much more recent than is now the case. The demise of the last major ice sheet in Scandinavia and of the smaller glaciers in northern Britain may be placed a

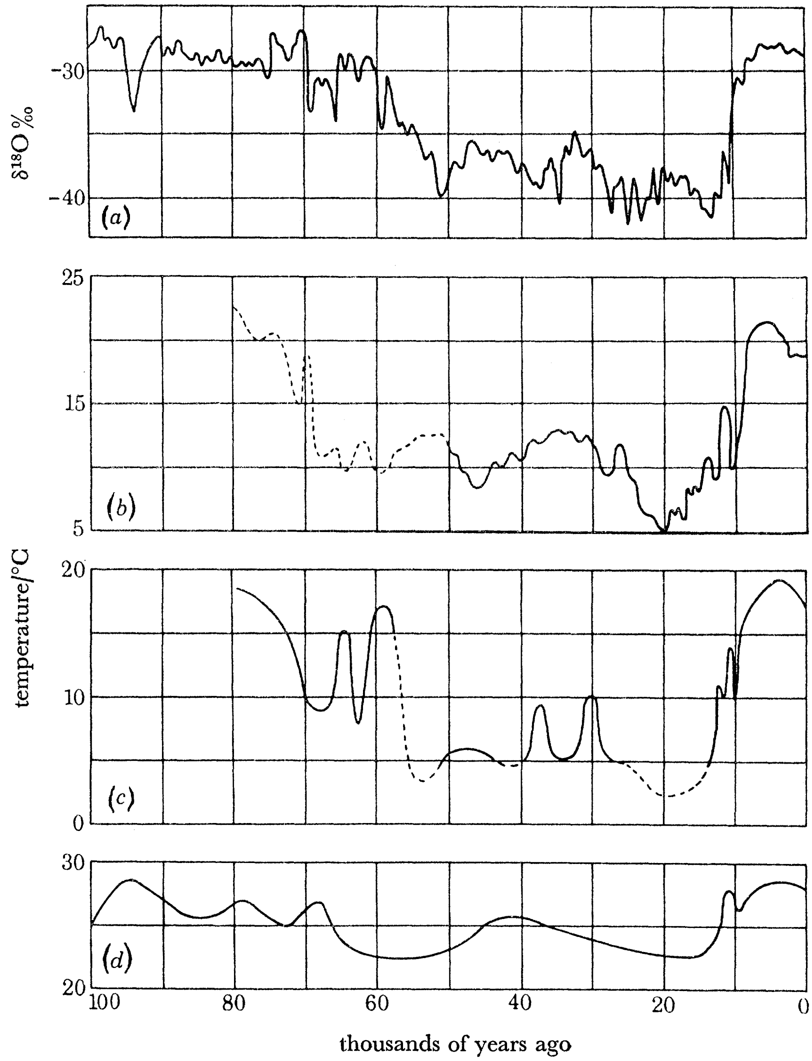


Figure 6. Variations of prevailing temperature during the last 100000 years: (*a*) N. Greenland (77° N, 56° W) – temperature changes indicated by differences in the $^{18}O/^{16}O$ oxygen isotope ratio ($\delta^{18}O$). A change of $\delta^{18}O$ by one part per thousand (‰) has been found to correspond to a change of mean annual temperature by 1.3 to 1.4 °C (Dansgaard 1964; Dansgaard *et al.* 1971). (*b*) Central Europe – summer temperatures deduced from pollen analysis (Gross 1958). (*c*) Netherlands – summer temperatures deduced from pollen analysis (van der Hammen *et al.* 1967). (*d*) Tropical Atlantic – annual temperatures of the surface waters derived by oxygen isotope measurements on the remains of surface-dwelling *foraminifera* identified in the bottom deposits (Emiliani 1955, 1961).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

little before 8000 B.C., and that of the last remnants of the ice sheet on the North American mainland, east and west of Hudson's Bay, perhaps as late as 3000 B.C. (Bryson & Wendland 1967).

(i) *Temperature*

The sequence of prevailing temperatures over the last 100000 years, through the last ice age and since, has been derived from various kinds of field data (see figure 6).

(*a*) For the surface waters of the tropical Atlantic – from studies of the remains of the minute biological organisms (*foraminifera*) in the deposits on the ocean bed (Emiliani 1961).

(*b*) For the summers in the Netherlands and in central Europe – by interpretation of the composition of the flora from pollen analyses (Gross 1958; van der Hammen, Maarleveld, Vogel & Zagwijn 1967).

(*c*) For the air over the ice-cap in northwest Greenland – from oxygen isotope measurements on the ice still present.

The results are remarkably consistent except as regards the timing of the fluctuations beyond the workable limit of radiocarbon dating 30000 to 50000 years ago. There is parallelism of most details of the changes from millennium to millennium in the last 15000 years. Not surprisingly, there are differences in the range of the variations in the different locations: the temperature range from ice-age minimum to postglacial maximum appears to amount to nearly 20 °C in northern Greenland, 16 °C in the summer temperatures in Europe, 5 to 6 °C in the waters of the tropical Atlantic; the decline of prevailing temperature in the last 4000 years is indicated as 1 °C in the tropical Atlantic and about 2 °C in the other places named.

Judged by the changes in height of the snow-line on the mountains, this range of temperature changes in the tropical Atlantic is similar to those which occurred widely in tropical and subtropical latitudes. A peculiarly great ice-age lowering of the snow-line (*last* glaciation) by as much as 1200 m in the eastern Taurus Mountains in southern Turkey, and by 1800 m in the Zagros Mountains (Algurd Dagh) near the border of Iraq and Iran (Wright 1961), is attributed to the combined effects of lower temperatures and a considerable increase of precipitation accompanying frequent cyclonic activity in a zone passing south of Europe. (These areas are close to where a number of early civilizations developed.)

The course of postglacial temperature changes is best established for northwestern and central Europe from botanical, and in later times documentary data, particularly for England (Lamb 1965*b*, Lamb, Lewis & Woodroffe 1966), where daily temperature readings are available for almost 300 years past, and have been carefully standardized by Manley (1959, 1961). Figure 7 shows the sequence derived for temperatures prevailing in the lowlands of central England in summer and winter over the last 20000 years. (There is a discrepancy, not yet resolved, regarding the summer temperatures 11000 to 15000 years ago indicated by the evidence of insects, broken line in the diagram, and studies of the vegetation by pollen analysis; but this need not concern us here.) The margins of uncertainty regarding the dating and temperature-interpretation of the botanical evidence are indicated on the diagram by the ovals, each of which represents the data relating to some régime that seems to have lasted for the duration indicated by the horizontal bars. The curves are drawn to indicate the probable course of the 1000-year average temperature. The dots within the last 1000 years indicate the individual century averages (derived by the methods reported in Lamb 1965*b*) and serve to indicate the range of the century-by-century variations; the decade values and the individual years, of course, vary more widely – the latter apparently, since 1680, show just 7 times the range of the

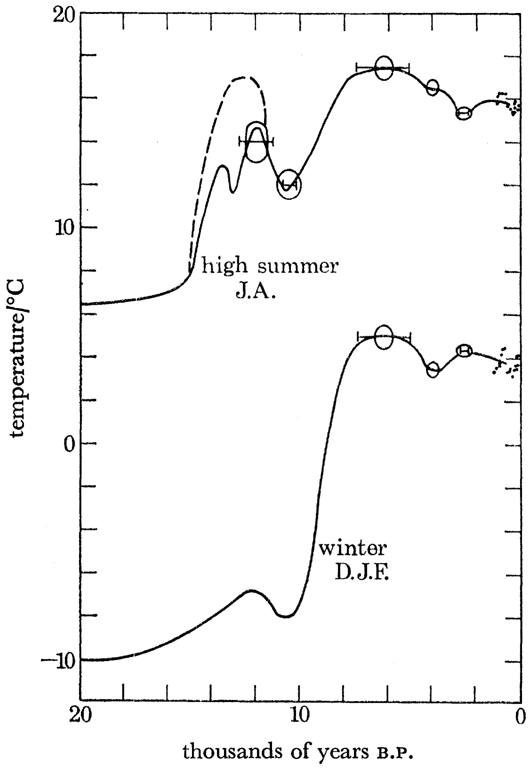


FIGURE 7. Variations of prevailing temperature in central England (lowland sites) over the past 20000 years. (Estimates mainly from botanical evidence.) *Oval plots* indicate the range within which the mean value derived from botanical data must lie, within the uncertainties of carbon-14 dating and temperature implications of the botanical data. Each plot represents the data of a well-marked régime which appears to have lasted for a period indicated by the horizontal bars. *Dots* indicate temperature values derived by statistical analysis of documentary weather reports (for the method see Lamb 1965*b*, 1972) and, in later times, directly from thermometer readings. *Broken line*: temperatures indicated by analysis of the beetle fauna (Coope, Morgan & Osborne 1971). *Whole lines*: estimated course of the thousand-year average temperatures.

century means of the last 1000 years. The variability in England, near the ice limit, in glacial times was probably three times as great, but is unlikely to have changed significantly in the last 6000 years, or rather more, since the geography of Europe became more or less as it now is. Moreover, England being exposed to prevailing winds from the Gulf-Stream–North Atlantic Drift water in the ocean in middle latitudes is likely to experience temperature changes which are fairly representative of a wide range of latitudes: within the past 100 to 150 years the temperature trends in England seem to have been always in the same sense as, and very close in magnitude to, the world average. This analysis confirms the diagnosis that the prevailing temperature level between 4000 and 1000 B.C. was mostly 1 to 2 °C above that in recent historical times.

(ii) *Sea level*

The melting of the great ice sheets that had covered the northern parts of Europe and North America caused a great ('eustatic') rise of world sea level. The most careful computations of the rise by Godwin, Suggate & Willis (1958), Shepard (1963) and Schofield & Thompson (1964) indicate that it amounted to 35 to 40 m between 7000 and 2000 B.C., an average rate of 70 to 80 cm a century: most of the rise took place between 7000 and 4000 B.C. During those times the North Sea was reconstituted much as we know it today, and many former coastal lowlands in other parts of the world became submerged. Schofield & Thompson's curves, seen in figure 8, indicate that the general level (mean tide level) around 2000 B.C. was probably 2 to 3 m higher than today. The building under Rameses II of a proto-Suez canal around 1230 B.C. may well be related to the level of the seas being at its highest at the end of the warmest postglacial times and the continued melting back of glaciers that went on during those times.

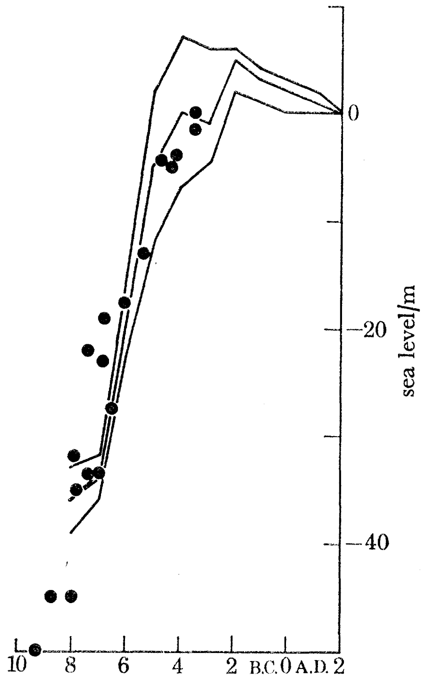


FIGURE 8. World sea-level changes in the last 12000 years. *Dots* – point estimates from widely scattered parts of the world, chosen for their tectonic stability; radiocarbon dated values (Godwin *et al.* 1958). *Curves* – calculated results from raised beach levels in Scandinavia, by identifying the local isostatic and general eustatic components of change at different places along the same former strand-line (Schofield & Thompson 1964). The middle curve is the most probable result. All the results came within the area bounded by the outer curves.

In those parts of the world that had been subjected to a great ice-load, postglacial times have seen a gradual 'isostatic' recovery of the Earth's crust resulting in local, or regional, rises of the land relative to the sea. In Scandinavia, and even in Scotland, this isostatic land-rise has over long periods overtaken the rise of world sea level, so that the land has continued to emerge despite the rising ocean. Only between about 6000 and 4000 B.C. in Scotland, and between 6000 and about 2000 B.C. in Norway, was the sea level rising relative to the land – in both these areas by about 10 to 15 m over the period named (see figure 7 in Donner 1970). From 4000 to 2000 B.C. sea level was approximately stationary. In the southern half of England and Wales and in the Netherlands a local sinking of the land relative to the sea is observed, and between East Anglia and Holland the sea now stands higher than it did about 4000 B.C., according to one careful analysis about 9 to 10 m higher (Churchill 1965).

In the Mediterranean (and perhaps elsewhere in the Near and Middle East) there have certainly been many erratic local changes of sea level, due to the tectonic instability of the region; but the region as a whole has experienced the world-wide changes to which figure 8 refers. Bloch (1970) has traced important effects of changes of sea level and of (evaporation) climate in the Mediterranean and the Near East on the salt industry, which was at certain times related to sea-shore installations (salt-pans) that were later submerged, and at other times related to sources inland, particularly the Dead Sea. He gives as phases of high general sea level 2200 to 1800 and 1500 to 1200 B.C., also around A.D. 400 and 1100 to 1500, and lowered sea-level 500 to 0 B.C. and around A.D. 700. Sea levels higher than those of today, derived from the data generally between about 3000 and 1000 B.C., presumably checked the maximum rates of discharge of which the rivers were capable and should therefore have tended to increase the river floods in the lower parts of the valleys in the Near and Middle East, and in India and China, as in all other parts of the world except those affected by isostatic uplift.

(iii) *Forest and grassland limits*

Pollen-analysis applied to sample deposits found in peat-bogs and past and present lake-beds has by now provided the knowledge from which a fairly reliable general survey of the history of forest limits and vegetation boundary movements over the great lowland expanses of Europe and northern Asia, as well as the eastern and central sectors of North America, can be given. In these regions the limits are generally thermally controlled. Figure 9 depicts the withdrawal southwards of the northern forest limit and of the limit of the broad-leafed trees (mixed oak forest) from the latter part of the warmest postglacial times in 3000 to 1000 B.C. to the present day. The readvance of the limit of permafrost (permanently frozen subsoil) in northern Asia is also shown. Recent studies in the relationship of the pollen-rain at the present day to tree populations (Andersen 1972) are making it possible to go further than before in reconstructing the actual forest composition from the pollen percentages of different species in past ages. From this, it appears that in the warmest postglacial times the forests in Denmark may have been dominated by lime (linden) trees and to some extent by elm: these species gave way from about 3000 B.C. onwards, beeches becoming very prominent in Denmark and oaks becoming the dominant element in most parts of the broad-leafed forest zone. The change seems to coincide with the first colder climatic phase which lasted perhaps a few centuries in Europe and also with the appearance of the first Neolithic farmers over wide areas; there is as yet no certainty as to how far the change in the forests should be directly attributed to climate or possibly to some activities of Man and his adaptation to a climatic crisis (see, especially, Tauber 1965, pp. 54–61; Frenzel 1966).

The greatest postglacial spread of forest to the Atlantic fringe of Europe seems to have been somewhat before the times with which we are mainly concerned and apparently included some woods or thickets of birch and willow, and even oak, elm, hazel, and perhaps pine, in the Shetland Islands between about 5000 and 3500 B.C., according to a radiocarbon-dated pollen stratigraphy in peat that is now below sea level (Hoppe & Fries 1965). In the Orkney Islands only birch, hazel and pine are known, from macro remains, certainly to have been present but were extensive, even at the northwest coast (Traill 1868,† Moar 1969*a*). There is evidence of similar woods or thickets in the Outer Hebrides, e.g. South Uist, so far undated by modern methods but thought to be from about the same period. And pines grew close to some of the

† Traill quotes a dramatic account by a local resident at Otterswick (59° 15′ N, 2° 30′ W), on Sanday in the northern part of the Orkney Islands, of how a prolonged NE gale in the winter of 1838 caused the sea to scour the sand from about 50 acres of the bay just above the low-water mark, laying bare a forest floor of 'black moss' and fallen trees (up to 2 feet in trunk-width) all lying in the same direction from SW to NE. The same forest remains were then found to extend for 6½ km across the shallow bay to Tuftsness. The forest had evidently grown close to the Atlantic shore of the time concerned and in a locality completely exposed to the ocean to the NW.

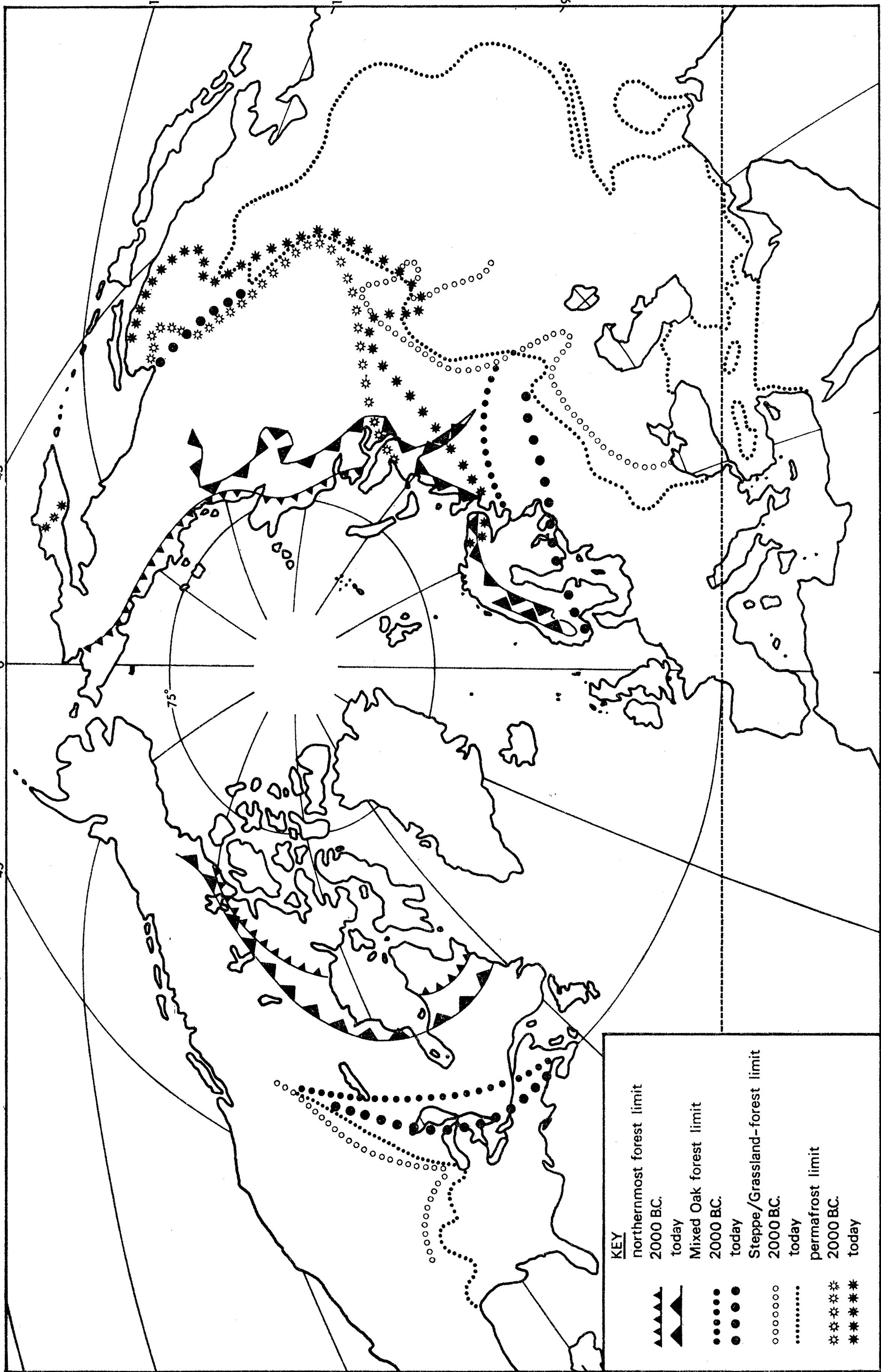


FIGURE 9. Forest limits on the plains of N. America and Eurasia about 2000 B.C. and at the present day. Compiled from works by Bryson & Wendland (1967), Frenzel (1966, 1967), Nejstadt (1957) and Nichols (1967*a*).

most exposed parts of the Atlantic coast of the Scottish mainland, in Wester Ross and Sutherland (Lamb 1964, 1965*a*). Though there was some decline of these woodlands from as early as 3500 to 3000 B.C. onwards (Moar 1965, 1969*b*), more rapid decline, which has been variously attributed to increased wetness, soil acidification and the beginnings of bog growth, possibly also to stronger winds, or to all these things, occurred between about 2600 and 1600 B.C. (H. H. Birks personal communication, Moar 1965, 1969*b*). Godwin (1956, p. 338) records that, as late as the Bronze Age, Cornwall, Wales and Ireland were forest-clad right to their western shores and to higher altitudes on the hills than any present woods.

The farthest northern extensions of the forests in the continental sectors, in both North America and Eurasia, are dated somewhat later, between about 3000 and 1500 B.C. This may be because of the long aftermath of the ice age in these sectors, particularly the slow withdrawal of the cold sea from the regions of land surface that had been depressed by the former ice load. In latitudes near 80° N, radiocarbon dating of driftwood left on the now raised beaches of Spitsbergen and the Canadian archipelago indicates that there may have been most open water about 4000 B.C., though similarly open conditions continued until perhaps 1500 B.C. (Blake 1970). In the fiords of northernmost Greenland the period of most open water was not until 2000 to 1600 B.C. (Fredskild 1969). Nichols (1970) deduces from pollen diagrams for the North-Western Territories that the onset of cooler summers in northern Canada may be dated about 1500 B.C., in good agreement with the time of change indicated in Greenland and elsewhere. There was a warmer phase in both countries between about A.D. 900 and 1100 to 1200. Throughout the times which we have been considering, the spruce (*Picea abies*) seems to have been spreading westwards across Finland and Scandinavia at the expense of the earlier established trees (Tallantire 1972*a*, *b*). The advance of the spruce to dominance from the small pockets which had existed from much earlier times in favourable sites throughout the region, is probably to be attributed to this tree's competitive advantage in long cold winters, and therefore may be taken as indicating a fall in the general level of winter temperature. The spread of spruce forest from the east which betokens this, as derived from pollen diagrams from sites all over Fennoscandia, was not a smooth, continuous process but took place in distinct steps: (1) around 3400 to 3000 B.C. to the Finnish–Russian border, (2) around 2300 to 2100 B.C. to much of southern and central Finland, (3) between 1600 and 1300 B.C. a slight further advance, (4) 1000 to 400 B.C. across all central Sweden, (5) between A.D. 250 and 750 over southern Sweden and (6) between about A.D. 1100 and 1400 in Norway across Trøndelag to Trondheimsfjord. At each of these stages a renewed decline of the winter temperatures may be suspected.

The vegetation changes so far discussed probably owe little or nothing to human interference. But in Britain and central and southern Europe from Neolithic times (say 4000 B.C.) onwards, recession of the forest was increasingly due to Man (Godwin 1956, p. 332 ff; Turner 1965*a*; Nichols 1967*b*; Pennington 1970).

In southern England, particularly in the inland districts near the chalk downs and the Cotswolds and Mendip Hills, human activity has been considerable ever since Neolithic times. A closely argued paper by Godwin & Tansley (1941) seems to have given a reliable picture of the vegetation with implications about the climate despite all the human interference. Oak and hazel were clearly present in some abundance near the chalk, and were the main species used as firewood by the Neolithic inhabitants around 3000 to 2000 B.C.; yew constituted 8 % of the charcoals analysed. But the evidence suggests that the trees were at the foot of the hills and on the slopes. The Neolithic people settled the chalk uplands, including Salisbury Plain, grew crops and kept sheep, and it seems likely, therefore, that the tops were already bare of trees. In the succeeding Bronze Age, the chalk plateau seems to have ceased to be used for settlement, though it was much used for grazing, for traffic and for burials: the implications of this archaeological evidence seem to be that the downs were already grassland and that the climate was drier than it had been earlier, in the Neolithic. The beautifully preserved form of the burial mounds could not have survived if their sites had been disturbed for long by the roots of woodland trees at any time since the barrows were made. There is more direct evidence of dryness of the Bronze Age climate in the digging at Wilsford, in the Salisbury Plain area, of a 33 m deep shaft, dated about the middle of the second millennium B.C.† to 1.5 to 2 m below the present water table‡ (Ashbee 1963, 1966). With the colder climates and increased wetness that set in from about 800 to 500 B.C. onwards, the early Iron Age peoples resettled the chalk uplands and tilled greater areas on the downs than ever before; it seems clear that the plateau remained largely bare of trees. Another type of archaeological evidence points to the same climatic sequence; wooden trackways were laid across the Somerset Levels (and other fens in the lowland areas of England), to keep open communications across the marshland when climatic conditions became wetter. The radiocarbon datings of these trackways are generally between about 3500 and 2500 B.C., and between 900 and 300 B.C. (see, for example, Godwin & Willis 1959).

Figure 9 also shows how the southern limit of forest, where broadleafed and mostly deciduous forest gives way to steppe, has shifted in the last 4000 to 5000 years on the plains of Eurasia and North America. In general, the steppe appears to have advanced, though the reasons for this are by no means clear: human action and increased windiness may have combined to clear the trees and reduce soil moisture at the margin of the forest zone. The great plains in the latitudes concerned east of the Rockies and in European Russia and Siberia had probably had a greater precipitation/evaporation ratio in glacial times, but the history of the Caspian Sea (see later, figure 10) suggests that any legacy of that moisture had vanished by about 5000 years ago. The water table may, however, have had a continued tendency to fall through most of postglacial time in the southern parts of these regions, as already noted (p. 203) in the Sahara and central and southern Asia, with the wastage of the subsoil and aquifer moisture left over from the climatic régimes of the last glaciation (or the moister stages of it).

To understand more about the vicissitudes of climate and vegetation, particularly in the more intricate terrains near, and in, the mountains of Asia, Africa and the Americas, it is necessary to use indirect methods to elucidate the general climatic régimes. The use of such arguments is fortified by the similarity of the main forest successions through postglacial time revealed by pollen-analysis of the stratigraphy of deposits in many parts of the world. This indicates, with broadly similar datings, a climax of warmth followed by a return to a cooler (or 'more boreal-type') environment – for example, in the Alpine foothills of northern Italy (see, for example, Beug 1964), Kashmir (see, for example, Singh 1963; Vishnu-Mittre 1966; Vishnu-Mittre & Sharma 1966), Japan (see for example, Tsukada 1967), and north and south America (Heusser 1966; Nichols 1967*a*, 1970) – like the successions observed in northwest and central Europe (see, for example, Averdieck & Döbling 1959; Firbas 1949; Godwin 1956;

† In the datings mentioned here, as elsewhere in this paper, corrections have been applied in accordance with the recent bristlecone-pine tree-ring calibration (Ralph & Michael 1967, Suess 1970*a*). Thus, the conventional carbon-14 date of the Wilsford shaft given as 3330 ± 90 years before present becomes about 1600 to 1700 B.C.

‡ 1.5 to 2 m below the present water table at its seasonal lowest, 9 m below the normal seasonal maximum at the present day.

Godwin, Walker & Willis 1957). Among the Anatolian mountains in northern Turkey Beug (1967) has found indications – a decline of beech and fir about 2000 B.C., while the oak, pine and juniper elements of the forests continued or gained ground – that the warmest postglacial millennia had been drier than the climatic régime after 2000 B.C. Farther north, at least in northwestern and central Europe, as also in the lower latitudes in Africa (the desert and the Nile), climates – though fluctuating – seem to have been becoming successively drier between 2500 and 2000 B.C.†

(iv) *Levels of inland waters – indications of moisture and cloudiness*

The changing levels of lakes and inland seas, which can be recognized by old strand-lines and dated either from historical records or radiocarbon tests on organic matter deposited, serve as a gauge of the changing balance between precipitation and inflow on the one hand, and evaporation and outflow on the other (always provided that the case has not been altered by erosion of the outlet, or by tectonic changes). The simplest cases are those like the Caspian Sea which has long had no outlet.

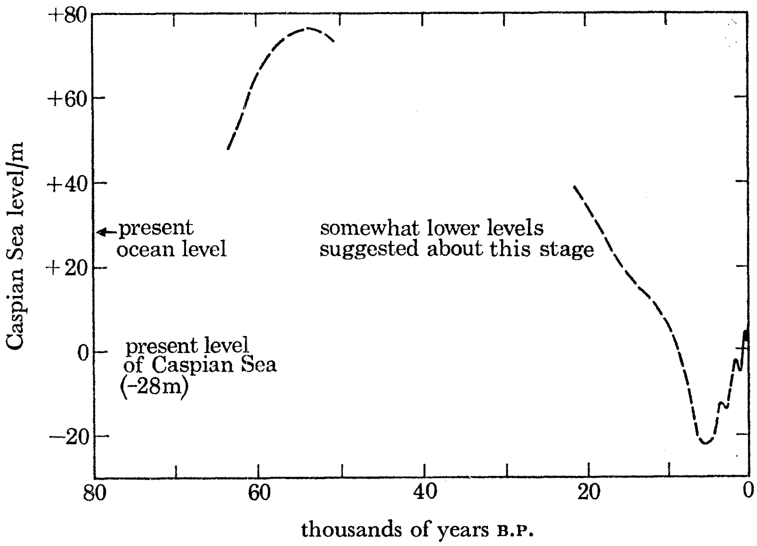


FIGURE 10. History of the level of the Caspian Sea. Scale in metres.

The history of the Caspian has been compiled by Berg (1934), Leontev & Federov (1953) and Nikolaeva & Han-Magomedov (1962) and is portrayed here in figure 10. The level was high in glacial times (when the area submerged was more extensive‡ than now), though it may have been somewhat lower in the long temperate period (interstadial) around 40000 years ago. The level was much lower than now in the warmest postglacial times between 8000 and 5000 years ago, and has risen in several stages since. It continued to be lower than now throughout the period from 3000 B.C. to A.D. 1000, though, as with the forest evidence from nearby Turkey, the tendency then was always towards increasing moisture. The Caspian, however, is supplied by

† The opposite trend, towards increasing moistness, detected in the region of Turkey and the Caspian Sea was presumably related to positions commonly occupied by a trough in the upper westerlies at that time.

‡ The Caspian Sea at present reaches, at its extremes, from about 37° to 47° N and 47° to 55° E. In glacial times, at its greatest extent, it reached 50 °N and joined with the Aral Sea to form a water surface stretching from 45° to 62° E in the northern part, with an overflow channel to the Black Sea. Its area approached twice that of the present Caspian.

the flow of the River Volga, and its level is therefore partly representative of the régimes farther north, in European Russia.

The long history of Lake Chad (near 13° N, 13° E) on the south side of the Sahara, as illustrated here in figure 11, has been put together from information supplied by R. E. Moreau (personal communication December 1963) and that published, with radiocarbon dates, by Grove & Warren (1968). This lake also was much higher than now in glacial times, even after erosion had greatly changed the then existing outlet to the Atlantic, and its extent was such that it might better be described as an inland sea (Mega-Chad, in Moreau's nomenclature). Its

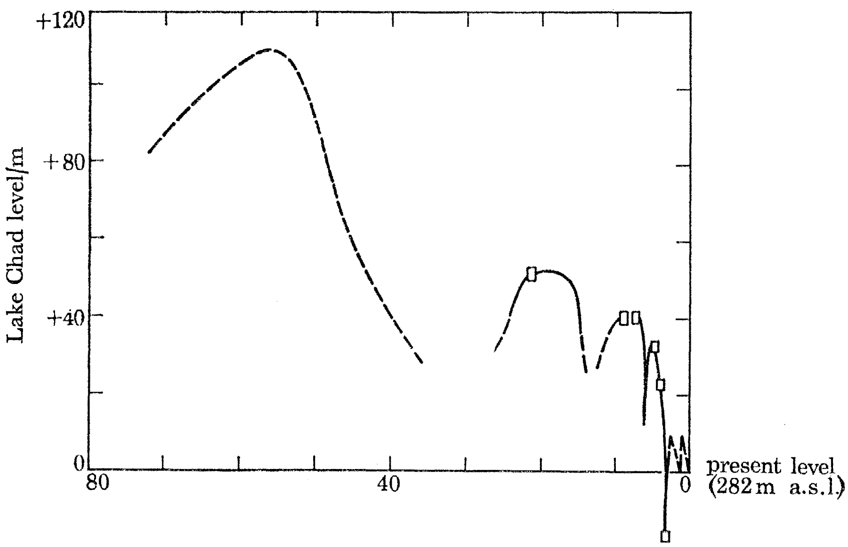


FIGURE 11. History of the level of Lake Chad. Scale in metres.

prevailing level has undergone a number of changes since, and still varies from year to year, though a net decline over the last 20000 years doubtless indicates the lowering of the water level in porous strata under the desert, since the end of the moistest régime at some stage during glacial times. (There is still doubtless some seepage through the underground strata: so Lake Chad is, strictly, not a lake without any outlet in the full sense that the Caspian is.) The history differs from that of the Caspian in that Lake Chad registered secondary high stands in the warmest postglacial times and, it is suggested, even in the more modest and short-lived warm periods of global climate about 1000 and 3000 years ago. The moisture maxima coinciding with these warm climatic phases are attributed to farther northward extension than now of the summer monsoon rains.

The comparative histories of the Caspian Sea and Lake Chad in recent millennia are made clearer in figure 12.

It is suggested that the Caspian may be taken as indicating moisture changes in latitudes 40 to 60 °N, at least in the Russian–west Siberian sector, and that Chad is representative of moisture changes in equatorial Africa. Butzer, Isaac, Richardson & Washbourn-Kamau (1972) have demonstrated that the dates of the high and low stands of Lake Chad and Lake Rudolf (3 to $5\frac{1}{2}$° N near 36° E) and four other lakes between 0 and 1° S in eastern equatorial Africa over the last 20000 years or more are in general agreement (see figure 13). The gross

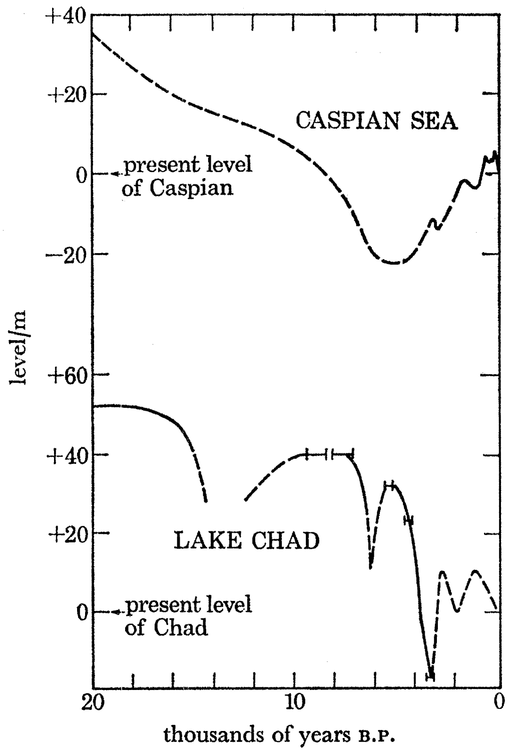


FIGURE 12. Variations of the Caspian Sea and Lake Chad over the last 20000 years compared. Scale in metres.

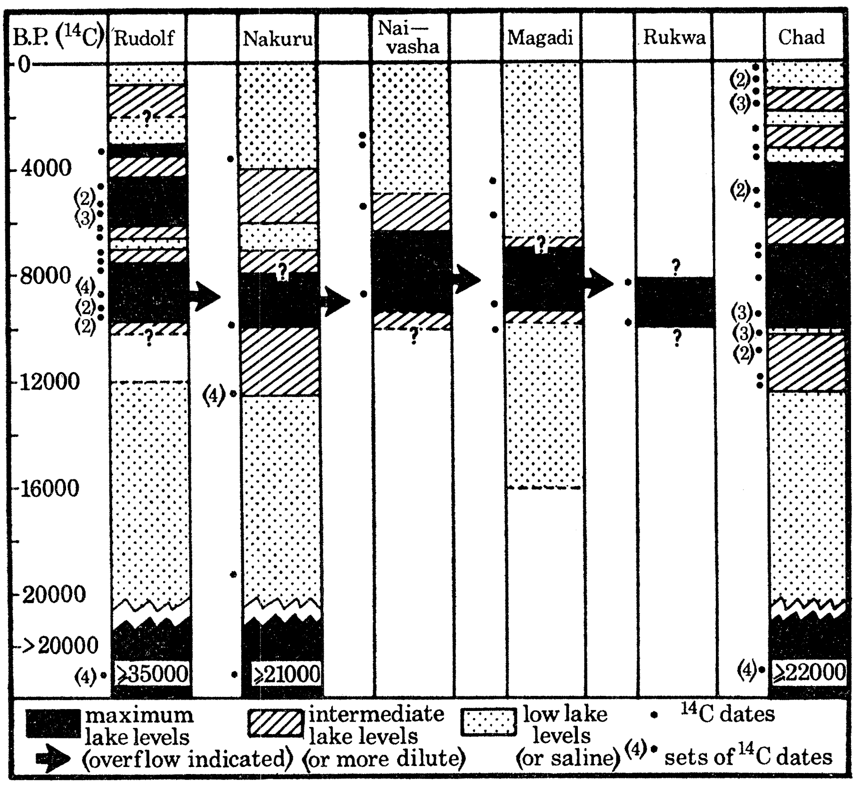


FIGURE 13. Fluctuations of the levels of lakes in tropical Africa that lack any outlet. (Reproduced from Butzer *et al.* (1972) by kind permission.)

differences between the high levels of Mega-Chad in the Ice Age, as well as around 8000 and even 4000 to 3000 B.C., with the water surface extending at times from 10° N 16° E to 18° N between 14 and 20° E, and its diminished state today are probably representative of the variations of general moisture available over northern Africa.

There may be a meaningful parallelism between the later rises of the level of Lake Chad and the spread of early settlements into the driest regions of southwestern Palestine around 6000 and 3000 B.C., reported by Blake (1969), each time followed by withdrawal in the succeeding centuries, in the latter case withdrawal for good.

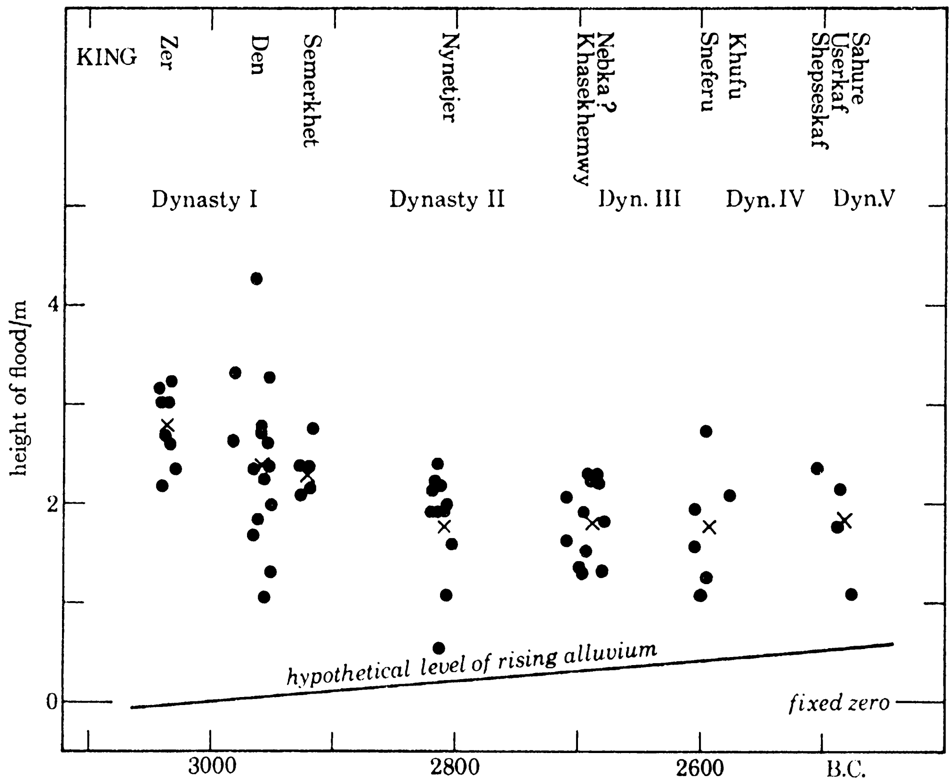


FIGURE 14. Height of the Nile floods in Egypt in sample runs of years in ancient times. (Reproduced from Bell (1970) by kind permission.)

The levels of the annual flood of the Nile river in Egypt have been recorded, either in inscriptions or documents, from before 3000 B.C. The lower Nile is supplied by two main branches of the river from farther south in Africa, the White Nile which emerges from Lake Victoria and drains much of eastern equatorial Africa, maintaining a fairly constant flow through the year, and the Blue Nile, which rises in the mountains of Ethiopia near 10° N and is fed by the summer monsoon rains. There is a record of the yearly low as well as the high level stages of the River Nile from A.D. 622 (Toussoun 1925). In interpreting this unique climatic record, it is necessary to allow for the progressive change of level due to the continued silting of the river bed and the flood-plain. This is usually taken, from the records of the last 1300 years, to amount to 10 cm per century. In reality, the rate of silting must have varied with the varying strength of flow of the river. Further uncertainties enter in over the type of gauge used in earlier times and its position. Nevertheless, Bell (1970, 1971) has shown that whatever assumptions are made about the datum, it is clear that the average flood level of the Nile in lower Egypt was always lower and less variable from year to year after about 2900 to 2800 B.C. than it had been in the centuries immediately before that (see figure 14). This decline of the flow of the Nile may reasonably be related to the end of the high-level stages of Lake Chad (figure 11) and the moist régime in subequatorial Africa that had obtained for some thousands of years previously.† It is also clear that there were several shorter periods marked by particularly low levels of the annual Nile flood, between 2180 and 2130 B.C., 2000 to 1990 B.C., soon after 1786 B.C. and again from about 1200 B.C. onwards. Several of these fluctuations are seen to be separated by an interval close to 200 years.

Deriving the distributions of climate and prevailing winds at different epochs

Any peculiarities of the global distribution of climates in any epoch are likely to be understood in terms of the peculiar features of the atmospheric (and ocean) circulation and anomalies of the local or regional condition of the surface (particularly ice-cover, waterlogging or parching), rather than by reference to subtle differences of the radiation available, which is always graded according to latitude and season. This is likely to be the case, even if the incoming radiation should differ from now, and be the ultimate reason for greater or less energy in the atmospheric circulation and a somewhat different pattern of heat transport from that now prevailing.

Attempts to reconstruct the atmospheric circulation patterns prevailing over the northern hemisphere at different stages of the last Ice Age and postglacial times have been made by Lamb *et al.* (1966, 1970). The method proceeded in a series of logical steps:

(*a*) Mapping the surface air temperatures prevailing in the warmest and coldest months, as indicated by the boundaries discovered for the occurrence of different species of flora (particularly the assemblages characteristic of different forest and vegetation zones) and of micro-organisms (mainly *foraminifera*) living in the surface waters of the ocean, whose thermal limits today seem to have been reliably determined. (See particularly Iversen (1944), West (1968, chapters 7 and 10) and the use made by Lamb *et al.* (1966) of the forest maps of Nejstadt (1957); for the ocean data see Emiliani (1955, 1961) and Imbrie & Kipp (1971).)

(*b*) Next, mapping the upper air temperatures, based on those that accompany such surface temperatures in comparable geographical circumstances today and hence deriving (via the air density) the vertical thickness of the lower half of the atmosphere.

(*c*) From the distribution of pressure of the overlying atmosphere defined by (*b*), the corresponding flow of the upper westerlies around the hemisphere, and the pattern and intensity of the circumpolar vortex, are then arrived at.

(*d*) Next, the tendency for cyclonic or anticyclonic development at all points of the map is computed by a method related to that used on instantaneous synoptic weather maps in numerical daily weather forecasting, based on the work of Sutcliffe (1947) on the development of surface weather systems.

(*e*) Finally the probable pattern of prevailing atmospheric pressure at mean sea level is

† Bishop (1965) reports that the lowest of a series of old strand-lines of Lake Victoria near the Nile outlet, just above the highest levels of the lake observed in modern times, was dated 3720 ± 120 radiocarbon years before present (about 2200 B.C. when the bristlecone pine-calibration correction is applied); and it is thought that the lake never reached that level since.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

sketched in from the analyst's experience by considering the derived distribution of areas of prevalent cyclone and anticyclone formation and the steering of these surface pressure systems by the mainstream of the upper westerly winds (the circumpolar vortex).

The January and July maps so derived for periods around 2000 B.C., 500 B.C. and in recent years (A.D. 1950s) for comparison are reproduced here as figures 15*a*, *b*; 16*a*, *b* and 2*a*, *b* respectively. The corresponding maps for 6500 and 4000 B.C. were published in Lamb *et al.* (1966). These maps may be read as maps of the prevailing winds, since under equilibrium conditions (i.e. the forces acting upon the moving air being in balance) the wind blows nearly along the lines of equal pressure, counterclockwise around the centres of low pressure in the northern hemisphere and clockwise around the high pressure centres.

The features indicated by these maps which seem relevant to our present discussions are:

(i) The weaker circulation and spread towards rather higher latitudes of the anticyclone belt around 2000 B.C. than in any period much after 1000 B.C. except probably for a few centuries in the early Middle Ages (approximately A.D. 950 to 1310, at longest). Around 4000 B.C. the anticyclonic influence already seemed to have spread to middle latitudes, almost as at 2000 B.C., but a more marked belt of westerly winds was indicated near 50 to 60° N. This difference probably means that around 2000 B.C. a greater frequency of blocked, meridional and rather stagnant circulation patterns was occurring: this suggestion would be in keeping with a high frequency of sunshine and quiet seas for sailing in latitudes as far north as 60° N. It would probably also account for greater variations (long- or short-term) of temperature and rainfall – attributable to fluctuations in the frequency and positions of blocking – in the co-called 'Sub-Boreal' period (3000 to 1000 B.C. approx.) than before about 3000 B.C.

(ii) The marked deterioration of climate which was affecting latitudes north of about 40° N by 500 B.C., according to many different types of evidence, is verified by withdrawal southwards of the anticyclonic influence, stronger and doubtless more often stormy winds, with the belt of cyclonic activity surrounding the polar cap having spread to rather lower latitudes than before. This would be accompanied by a considerable increase in cloudiness in the latitudes affected, particularly in the fifties, and in all those parts of Europe exposed to the increased westerly and northwesterly winds.

The features of this deterioration – i.e. lower temperatures and increased windiness – which was taken as defining the onset of the so-called 'Sub-Atlantic' climatic period in the older European literature have continued more or less to the present time, though with century to century variations which almost amounted to a short return of the Sub-Boreal warm climate in the early Middle Ages and a much colder climate associated with more blocking and a lower latitude of the cyclonic activity around the seventeenth century A.D.

When the average latitude of the subpolar low-pressure belt and that of the subtropical high-pressure belt in the European sector (longitudes 0 to 30° E) shown on the charts of this series are plotted against time, as in figure 17, the main trends are seen more clearly. This diagram brings to light a degree of parallelism between the latitude variations of these features and the changes of prevailing temperature (cf. figure 6), particularly in winter. Only the long-term changes, however, are reliably indicated in this way: analysis of the century-by-century (and shorter-term) variations of circulation régime within the last millennium shows that the varying incidence of blocking situations (with high pressure in the zone 50 to 70° N) may introduce wide variations of the latitudes of highest and lowest pressure averaged over periods as long as 20 to 30 years and perhaps longer. Indeed, a recently completed study by Bryson, Lamb & Donley

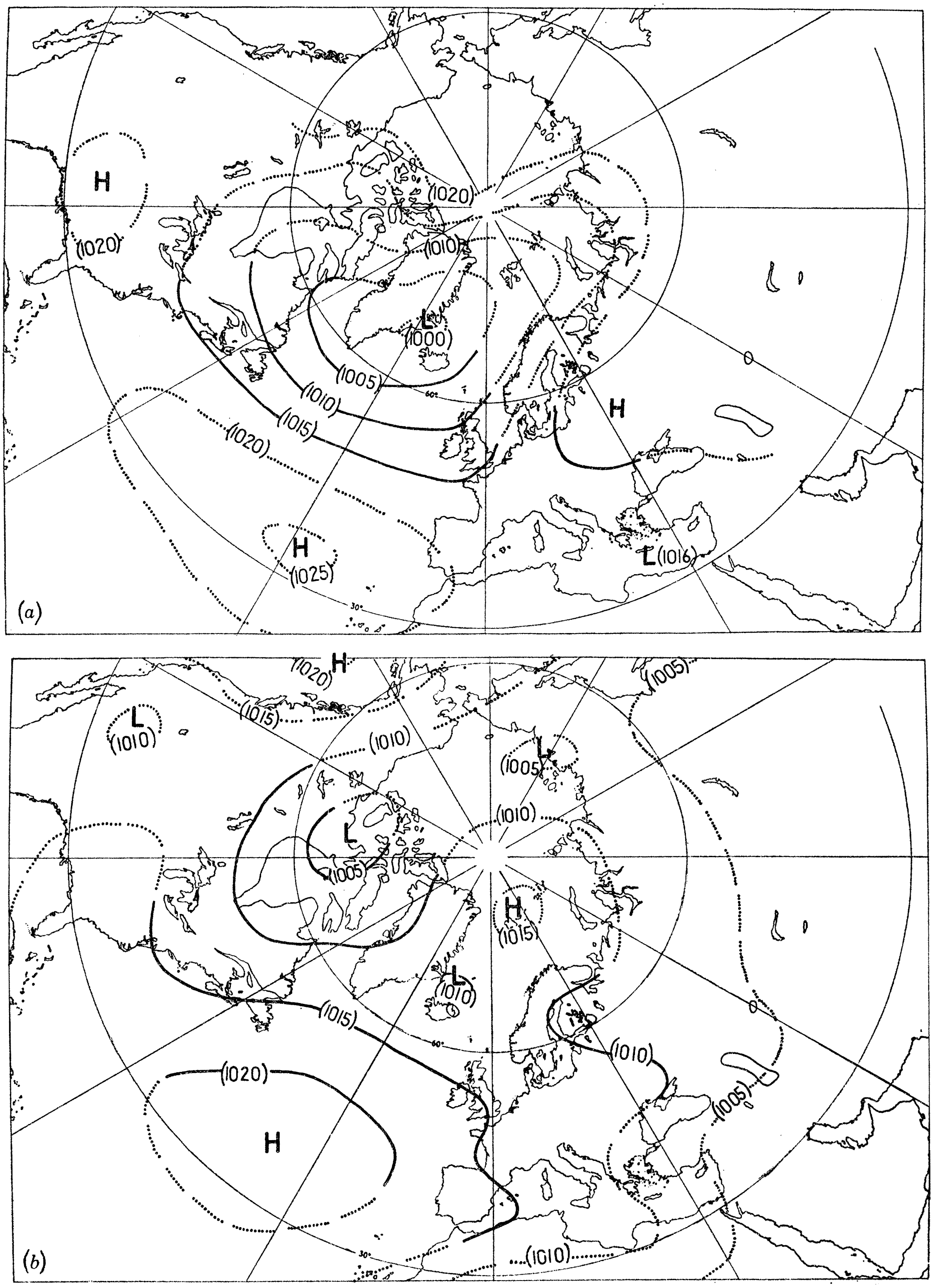
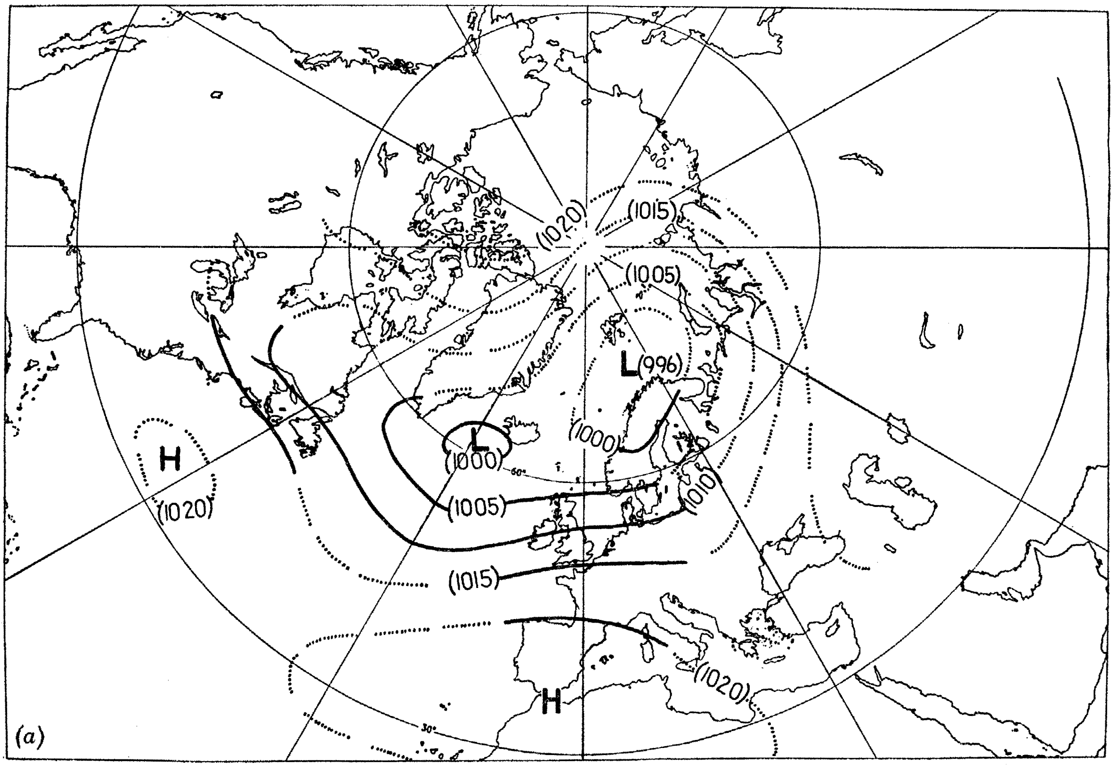


FIGURE 15. Average atmospheric pressure distribution at sea level derived by Lamb *et al.* (1966) for times around 2000 B.C.: (*a*) January, (*b*) July. Figures give suggested pressure values in millibars. Prevailing winds blow counterclockwise around the areas of low pressure, clockwise around areas of high pressure; the wind at the surface usually blows at an angle of 20 to 40° to the line of the isobar, i.e. blowing inwards towards the lower pressure.



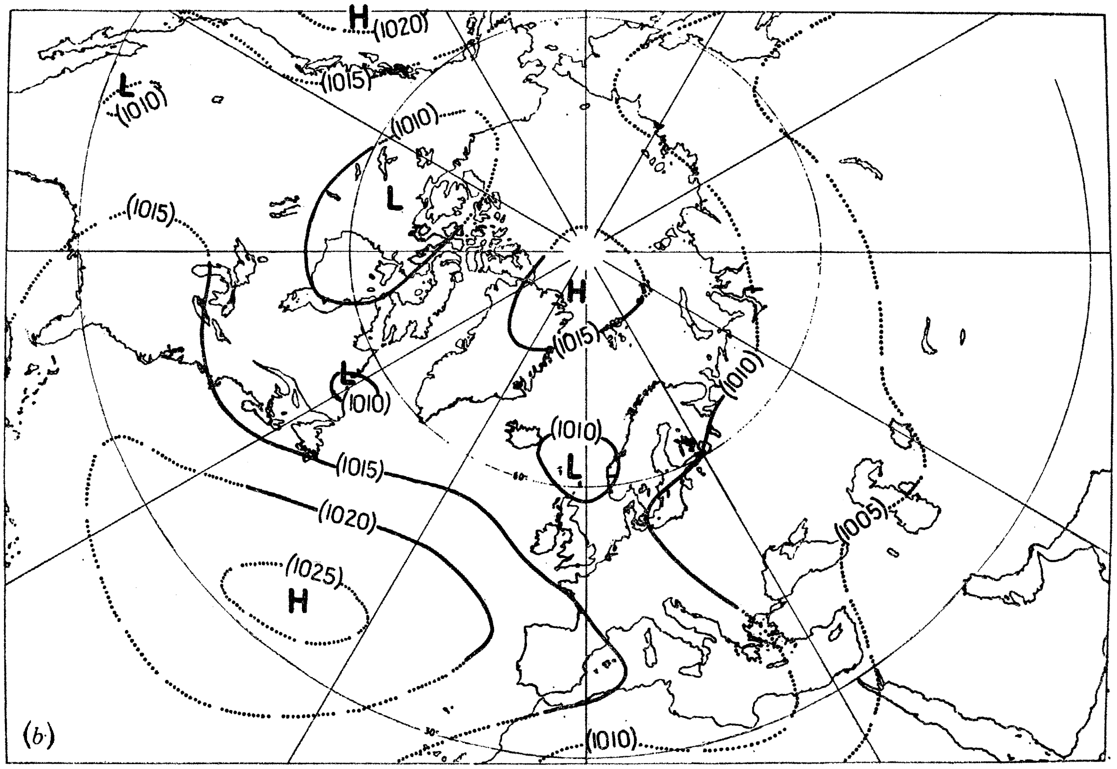


FIGURE 16. Average atmospheric pressure distribution at sea level derived by Lamb *et al.* (1966) for times around 500 B.C.: (*a*) January, (*b*) July.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(so far unpublished) of patterns of variation† of the northern hemisphere atmospheric circulation has built a case for believing that for some centuries around, and after, 1200 B.C. circulation patterns very like the particular, partly meridional pattern that characterized the 1954–5 winter were either abnormally frequent or, perhaps, the dominant situation.

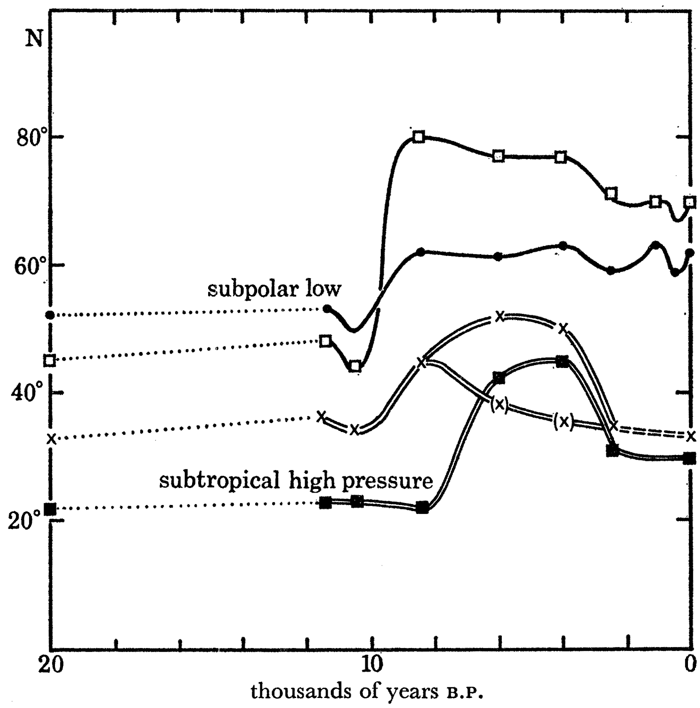


FIGURE 17. Average latitudes of the subpolar low-pressure belt and subtropical high-pressure belt in longitudes 0 to 30° E and their variations over the last 20000 years. □, ×, winter (January); ●, ■, summer (July). (Derived from charts by Lamb *et al.* 1966, 1970.)

The high periods of the Mayan and Aztec civilizations in central America, respectively in the first nine centuries A.D. and 1300 to 1500, may be seen as periods of climate either close to the average of the last 3000 years or below that average (especially in the eighth and fifteenth centuries) in terms of temperature and general latitude of the subtropical high-pressure belt. They may therefore have been drier in the latitudes of Mexico and Yucatan than the warm centuries of the early Middle Ages which apparently coincided with the Dark Age in central America that separated the flowering of these two cultures. In the warm centuries the intertropical convergence, and its associated clouds and rain, probably ranged farther north than in the colder periods.

Some evidence of the succession of climate and circulation régimes over the southern hemisphere during the last glaciation and through postglacial times has been given by Auer (1960, see particularly the discussion pp. 533–538), Derbyshire (1971) and Hastenrath (1971).

† Empirically found eigenvectors of the mean sea-level pressure distribution, from Kutzbach (1967), were used. The 1954–5 winter pattern was dominated by an eigenvector associated with more frequent than usual surface northerly and northwesterly winds from the Norwegian Sea to the western Mediterranean (and a sharp upper cold trough with its axis from the Baltic to Sicily – the other two winter-time cold troughs, over eastern Asia and Canada, were also sharper than usual) and abnormal development of high pressure over all northern Siberia, with a ridge extending towards the eastern Mediterranean and covering all southwest Asia. Under these conditions, excess warmth and drought developed over much of Greece, Asia Minor and neighbouring areas to the south and west.

The fluctuations of climate in early civilized times

As indicated on p. 207, the ranges of year-to-year variation of temperature (and, it is reasonable to suggest, those of rainfall) have probably not differed by more than a factor of 2 from their present values at all times within the last 6000 years in England, or indeed in most parts of the world except the Arctic, the northern Baltic and Hudson's Bay area (where the distribution of land and sea has changed), and in some mountain areas where the extent of glaciation has undergone considerable changes.

Reference has also been made in the preceding pages to longer-lasting fluctuations of climate, over a few decades, or in some cases a few centuries, superposed on the long-term trends. It is with these fluctuations that this section is concerned. Workers with various types of field evidence have commonly regarded the Sub-Boreal climatic period, between 3500 or 3000 B.C. and 1000 or 500 B.C. as marked by secular fluctuations of temperature and rainfall, at least in middle latitudes, of significantly greater amplitude than the earlier part of the postglacial warmest era. The most marked variations generally indicated are a cooler period of several centuries duration that defined the beginning of the Sub-Boreal (Frenzel 1966) and a period (or periods) of extreme dryness, at least in much of northern Europe (Brooks 1949, p. 298; Godwin 1956, pp. 227–228), towards its close. The period of great drought in Iran, Asia Minor, the eastern Mediterranean and, probably, in parts of Greece (Carpenter 1966) for some centuries from about 1200 B.C. onwards may be regarded as one of these fluctuations.

The evidence of drying out of the bogs for 200 to 300 years in late Sub-Boreal time, about 1000 B.C., and perhaps at other earlier stages between 2500 and 1200 B.C., in England, Scotland, also in some places in Ireland (Jessen 1949, p. 259; but see also Mitchell 1956, pp. 238–244), and other parts of northern Europe, includes stumps of birch and pine in the peat (Godwin 1954; Jessen 1949), trees which evidently spread onto the bog surface at that time. Close above the layer at which these tree-stumps are now buried is peat which is shown by sequences of radiocarbon dates to have grown rapidly, in west Wales with extreme rapidity (90 cm of peat formed in about 300 years from around 700 to 400 B.C. in Tregaron bog, according to Turner (1965*b*)). This 'recurrence surface' marking renewed onset of bog growth, manifestly in a wetter climate with cooler summers, and dated around 500 B.C., is found over much of northern and central Europe, where it is widely known as the *Grenzhorizont*. A sequence of similar recurrence surfaces, dated about 2300 B.C., 1200 B.C., 500 B.C., A.D. 400 and A.D. 1200 was recognized in the Swedish bogs by Granlund as long ago as 1932, and most of these seem to be traceable in widely separated areas of Europe. The dates have stood up well to comparisons with later radiocarbon tests; though Tauber (1965) gives 2200 B.C. for the earliest one, and A.D. 1250 to 1300 may be a more widely representative timing for the last of the series.

Most peat bogs show a stratigraphy of recurrence surfaces overlying peat layers heavily decomposed by drying out and darkened. Additional recurrence surfaces are found in the bogs in many parts of Europe. In many areas local factors confuse the sequence. Differences of bed-rock topography and drainage underneath the peat vary the sensitivity of different parts of the bog surface to changes of the evaporation/precipitation ratio and so introduce a spread of dates into the responses of different areas to any general change of climate. In Ireland, particularly, there are additional recurrence surfaces, some of them quite localized, perhaps because of the country's immediate exposure to moisture-bearing winds from the Atlantic; this is also the likeliest reason why the timing of the main groups of recurrence surfaces (neatly summarized

Table 1. Climatic fluctuations registered in the stratigraphy of peat bogs and some parallel data

Note. Dates derived from radiocarbon measurements are rounded approximations, after correction by comparison with Egyptian and Scandinavian varve chronologies and using the calibration curves published by Ralph & Michael (1967) and Suess (1970*a*). Those radiocarbon dates the most probable value of which required correction by more than a few decades are marked *

Ireland (data from Jessen 1949; Mitchell 1956; Smith *et al.* 1971)	Britain (data from Godwin 1956; Godwin & Willis 1959)	Scandinavia (data from Granlund 1932; Tauber 1965)	Germany and Central Europe (data from Frenzel 1966; Overbeck *et al.* 1957)	Greece (after Carpenter 1966)	Nile (data on annual floods in Egypt from Bell 1970, 1971)
			3400–3000 B.C. cold phase		
ca. 2800* B.C. wetter, peat growth setting in		2800 B.C. wet phase beginning			
		ca. 2500 B.C. probably dry			
ca. 2400 B.C. becoming wetter, pines decline, bog growth increasing					
ca. 2200 B.C. further spread of bog growth		2200 B.C. wet phase beginning			
					2180–2130 B.C. low floods
ca. 2000* B.C. further spread of bog growth					
					2000–1990 B.C. low floods 1786 B.C. ff low floods
ca. 1500 B.C. renewal of bog growth				1400 B.C. ff. adequate moisture	
	ca. 1200 B.C. onset of wetter conditions	*ca.* 1200* B.C. wet phase beginning	1250–1200* B.C. wet phase	1230–1100 B.C. cultural decline and depopulation, possibly indicating drought: worsening after 1100 B.C.	*ca.* 1200 B.C. low floods phase sets in again
ca. 800 B.C. renewal of bog growth			*ca.* 900* B.C. wet phase beginning		
	ca. 700–500 B.C. conditions becoming wetter	*ca.* 500 B.C. wet phase beginning	*ca.* 600 B.C. wet phase beginning		
			ca. 400 B.C. wet phase beginning		
	ca. 350–100 B.C. wet conditions		*ca.* 150–100 B.C. wet phase beginning		
B.C. —— A.D.	60 B.C.–A.D. 50 becoming drier				
		A.D. 400–500 wet phase beginning	several indications of further recurrence surfaces (regrowth of bogs) in N. Germany A.D. 565–595 and A.D. 690–770		
ca. A.D. 500 renewal of bog growth					
		A.D. 1200–1300 wet phase beginning			

in a diagram by Mitchell 1956, p. 238) differs from the rest of Europe. In Ireland, the main dates when bog growth set in again, after a drier period in which the peat had become humified and darkened, seem to have been about 1500 B.C., 800 B.C. and A.D. 500. Another type of local or regional peculiarity affects the sequence of recurrence surfaces near the Baltic in Russia and Finland, where the water table varied largely in accordance with the changes of sea level that depended on the balance between the world-wide post-glacial rise of sea level and the strong isostatic uplift of the land surface which had underlain the ice-sheet. Nevertheless, Khotinsky (1971) reports that similar decomposed peat layers with lighter-coloured peat and regrowth above a boundary horizon are found in peat bogs throughout the forest zone of the Russian plain, and in western Siberia, as well as in the Far East and Alaska; some of these recurrence events are dated as far back as the so-called 'Atlantic' climatic period, well before 3000 B.C.

Table 1 is an attempt to summarize the data on fluctuations of climate within these millennia from a limited number of reliable sources for Europe and the Near East. The resulting survey appears self-consistent, but must be regarded as tentative in detail until many more firm datings are available. Correction of the radiocarbon dates by applying the calibration adjustments suggested by the curves published by Ralph & Michael (1967) and Suess (1970*a*) has brought many of the dates into straightforward agreement with the dates given for events elsewhere in Europe which had not been arrived at by carbon-14 tests, and has thereby simplified the apparent message of the table; but the adjustments amount to several hundred years before 900 B.C. and further confirmation seems desirable.

It seems safe to conclude that there were well-marked wet, and presumably cloudy, phases in northern Europe during these millennia, those which set in about 2200, 1200 and 500 B.C., as well as in A.D. 1250 to 1300, bringing the sharpest deteriorations and being the most widely registered. It appears that there may have been a 'preferred' (i.e. most common) interval of 200 or 400 years between successive wet phases. There seem to have been several centuries of drier conditions at least between about 1800 and 1400 B.C., possibly from 2000 B.C. or soon after, till 1200 B.C., and, at a more modest level, from about 80 to 60 B.C. till A.D. 550. Since drought in Greece can occur with westerly winds over Europe, especially if these alternate with the occasional spread of anticyclonic conditions over southern and eastern Europe and the Mediterranean, Carpenter's (1966) suggestion that drought set in in Greece at the time of the decline of Mycenae, from 1230 B.C. onwards, may well concur with a long period of wetness in northwestern and central Europe, accompanied by frequent westerly and northwesterly winds over Britain and Scandinavia. Evidently, the situation over Greece in the centuries between 1230 and 800 or 750 B.C., when the land remained to a considerable extent depopulated and in cultural decline (if the cause was drought) was more frequently anticyclonic than during the next wet phase in northwestern and central Europe around 500 to 100 B.C. This latter period probably more often saw the spread of cold air from the north to all parts of Europe: there were considerable glacier advances, though rarely matching those of A.D. 1550 to 1850. There is scattered evidence of a marked warming in Europe from about 100 B.C. onward.

Figure 18 reproduces the analysis, thought to represent rainfall, by Schostakowitsch (1934) of the remarkable series of annual layers in the mud deposit on the bottom of a small salty lagoon on the west coast of the Crimea. The layers are presumed mainly due to the run-off from the land caused by the heavier rainstorms; but most of the layers are only a few millimetres thick, and some may have been missed in the counting. The earliest layer was counted as 2294 B.C., but could have been slightly earlier. A rainfall scale suggested by Brooks (1949,

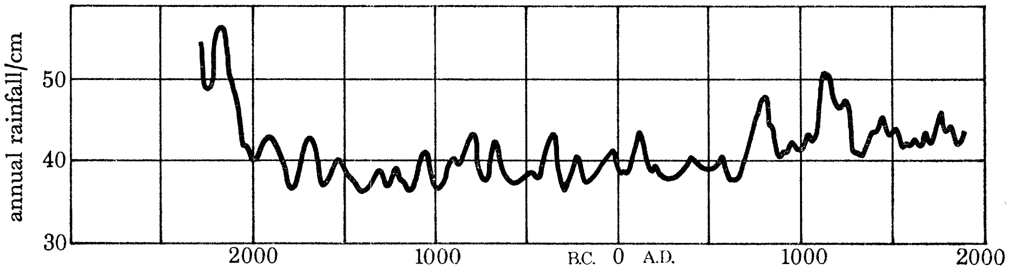


FIGURE 18. Rainfall variations in the Crimea since about 2300 B.C. as indicated by the thickness of the yearly mud layers in the bottom deposit of Lake Saki, 45° 07′ N, 33° 33′ E. (From Schostakowitsch (1934), with rainfall scale suggested by Brooks (1949).)

p. 299) has been added to the diagram. This record suggests (*a*) that variations occurring 4 to 6 times in a thousand years are important, (*b*) that a few centuries between A.D. 800 and 1250 represented a temporary return to moister conditions rather as they were before 2200 B.C. The fluctuations of rainfall in the Crimea appear often inverse to the changes in the prevalence of ground moisture found in northern, western and central Europe: this lake indicates dryness setting in about 2200 B.C. and no return to the former level except in the early Middle Ages. Particularly dry spells occur around 600 to 500 B.C. and a sharp return to drier conditions about A.D. 1250, both being times of marked wetness setting in (and renewal of the growth of the peat bogs) in western and northern Europe.

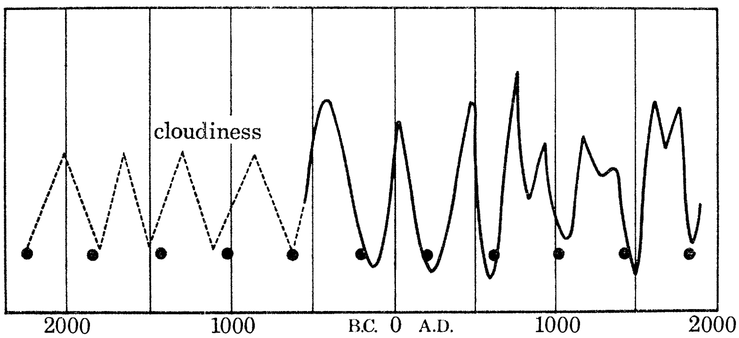


FIGURE 19. Variations of night cloudiness in latitudes about 30 to 50° N since 2300 B.C. indicated by Link's (1958) analysis of the frequency of discoveries of comets.

One other derived climatic series covering the whole time from 2300 B.C. to the present is illustrated in figure 19. Link (1958) has surveyed separately the available collections of reported discoveries of comets by observers in China and in western countries. The number of comet discoveries per century depends on:

(i) k, the number of comets actually within observable range of the Earth.

(ii) C, the frequency of cloudless nights, so that the number of comets visible in practice is Ck, where C is expressed as a fraction.

(iii) h, the human social or 'cultural' factor, describes the observation skill of the existing state of civilization; so that, with h expressed as a fraction, hCk is the number of comets actually observed and of which records were kept.

When the number (N) of comet discoveries per century ($N = hCk$) is plotted on a graph against the date, the resulting curve shows a sequence of waves superposed on a generally upward trend. The waves are in remarkable agreement in China and the West (for the period from 500 B.C. onwards for which continuous curves for both areas can be drawn). The level of the curves represents the human skill: this and its upward trend differs as long as the two communities were isolated from each other, being at first higher in China and after the ninth century A.D. higher in the West. Thus, the long-term mean level of the curve corresponds to the value of h, the human factor. Link therefore plotted graphs of N/h, thus eliminating the human factor, and obtained curves which showed only the waves. And since $N/h = Ck$, if k is (in the long-term) constant, these variations (similar in China and the West) must represent variations of night cloudiness in latitudes about 30 to 50° N. This is the curve seen in figure 19, plotted so that cloudiness increases as the curve rises. Groups of comet discoveries make it possible to place the minima of the curve as far back as 2300 B.C. The curve suggests a fairly regular oscillation, of period length about 400 years; the detail after A.D. 600 points to the possibility of a superposed oscillation of period 200 years. Such indirect and incomplete data cannot be regarded as establishing identity with a periodicity affecting weather data, and glimpsed in the Nile data and the apparently rather more irregular fluctuations of the lake in the Crimea which we have shown. But all these fragments suggest there may be a single underlying phenomenon. Link's suggestion was that the fluctuations were of solar origin, and there may be some support for this in the history of variations of radioactive carbon in the Earth's atmosphere which has since come to light (Stuiver 1961; Suess 1970*b*).

Concluding summary

The climatic situation between about 3000 and 1000 B.C. differed from today's in at least a few ways about which the evidence seems strong enough to speak with assurance. In particular

(i) Conditions seem generally to have been warmer, at least in summer, and more anticyclonic than now, presumably implying a greater frequency of clear skies and less frequent stormy winds, especially in middle latitudes – the difference was probably most marked between latitudes 40 and 60 or 65° N.

(ii) In subtropical latitudes, especially between about 30 and 40° N, there was probably somewhat more rainfall than now, and perhaps a less marked division of the year into dry and rainy seasons, though longer-term rainfall fluctuations involving runs of drought years separated by long periods with more frequent rain and cloud were important. A 200-year oscillation seems to have underlain at least some of the most severe of these fluctuations. At other times a 400-year spacing between similar fluctuations is apparent.

(iii) The equatorial rains seem to have ranged rather farther north than now in their seasonal migration for some long time ending about 2900 to 2800 B.C.: while this régime lasted, it presumably constituted a regular monsoon rainfall in Africa and SW Asia reaching to about 20° N, and an erratic incidence of more rainfall than now even farther north.

(iv) There was more subsoil moisture than now, and presumably more numerous and more extensive oases, in the present deserts and arid lands generally, partly as legacy of the climates of earlier millennia.

In consequence of these differences, there was more vegetation than now in the present arid regions, which even included forest in some areas that are now desert, though this vegetation was becoming increasingly vulnerable to human interference as climates became drier in tropical and subtropical latitudes and the soil moisture level sank (particularly in open country).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Forest also extended farther north than now, and nearer the coasts of Europe that are most exposed to Atlantic gales: recession of the forest from the most exposed positions was beginning quite early in the millennia here discussed, particularly from the Atlantic coasts, presumably due to climatic fluctuations involving increased windiness. Elsewhere, the main forest recession was probably after 1000 B.C., when the prevailing temperatures also seem to have dropped rather sharply. For some centuries about 600 to 400 B.C., but perhaps with forerunners as early as about 1600, 1200 and 800 B.C., and some further incidents as late as 120 to 100 B.C., there was evidently a particularly inclement period, with great wetness and frequent westerly and northerly or northwesterly storms near the Atlantic coasts, and penetration of the western Mediterranean also by colder and occasionally disturbed conditions.

The chalk uplands of southern England seem to have been grassland essentially bare of trees from as early as 2000, or even 2500 B.C., perhaps basically due to Man's activities, though a sequence of moisture changes can be traced, with mostly drier climate in the second millennium B.C. than before or after.

Meteorological knowledge and modern understanding of the behaviour and dynamics of the atmosphere can now be applied at such different levels of elaboration to the reconstruction of past climatic conditions that they amount to a variety of techniques, which contribute in quite different ways to the interpretation of past climatic régimes. The methods employed in this paper, and advocated by the present writer elsewhere, make the minimum necessary use of theory to derive the simplest outline picture of the complete pattern of flow of the atmosphere over the northern hemisphere, from the scattered factual data on prevailing surface conditions supplied by other branches of science and learning. In this quest for knowledge of the past, there is no room for barriers between the arts and sciences, since contributions from the most diverse studies and fields of expertise are needed. There is indeed a danger with the most sophisticated theoretical constructions of atmospheric models (in which the abilities of computers of great capacity are employed to take account of action and reaction and second-order effects), that the elaborate computation may go too far beyond our real knowledge of the detailed impact of past environmental conditions upon the atmosphere. If our reconstructions of past climates are to be realistic, there is a continuing need for all those field studies, and for all those attempts to cull relevant data from ancient documents and inscriptions, which can contribute facts about the actual conditions at an ever greater number of points on the map and at ever closer, and more closely dated, intervals of time.

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