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THE EARLY MEDIEVAL WARM EPOCH AND ITS SEQUEL

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SUMMARY

Evidence has been accumulating in many fields of investigation pointing to a notably warm climate in many parts of the world, that lasted a few centuries around A.D. 1000–1200, and was followed by a decline of temperature levels till between 1500 and 1700 the coldest phase since the last ice age occurred. There has been some controversy as to whether this climatic variation was great enough to be significant in connection with the balance of Nature or the economy of Man. It is time to marshal the evidence and attempt a numerical assessment of the climatic values involved in some area for which there are enough data to permit it. This is attempted here and provides an illustration of how data from the realms of botany, historical document research and meteorology may be used to confirm, correct and amplify each other.

Changes of prevailing temperature and rainfall in England between periods of 50–150 years duration around 1200 and around 1600 are found which, on all the evidence at present available, probably amounted to 1.2–1.4°C and 10% respectively. Changes in some seasons of the year may have exceeded these ranges of the annual mean. The changes indicated are small enough to account for earlier impressions in some quarters that there has been no significant change of climate in the last 2,500 years, yet they are big enough to be surprising in terms of previous meteorological knowledge and undoubtedly upsetting for the human economies of those times (and perhaps of *any* time).

It is by quantitative assessment of climatic values for epochs, such as the one here treated, for which some sort of extreme character is indicated by reliably dated evidence, that palaeoclimatology may hope to progress. The time-scale of the epoch here studied appears similar to that of several earlier climatic oscillations of known importance to the history of the European fauna and flora, which for obvious reasons cannot be submitted to equally close meteorological analysis. It is essential that the geographical distribution of climatic values arrived at, should be examined (as is done here) for consistency and the possibility of a

reasonable interpretation in terms of the condition of the wind and ocean circulations.

INTRODUCTION

The main stages of post-glacial climatic history in Europe, the warmest epoch generally known as the "Climatic Optimum" (e.g., GODWIN, 1956) from about 5000 or 6000 to 3000 B.C. (comprising the latter part of the "Boreal" and the whole of the "Atlantic" climatic periods of the older nomenclature), and the decline that introduced a cooler, stormier regime (the so-called "Sub-Atlantic") around 500 B.C., are well-known; though they still await thorough meteorological treatment. Till recently, it was widely held that the European climate had undergone no significant variations since that for the last 2,500 years or so the climate had been effectively constant or stable. Following the old nomenclature developed by the botanists BLYTT (1882) and SERNANDER (1910, 1926), all these years are still sometimes ascribed to the "cold and wet" Sub-Atlantic period. Now that several carefully standardized 150–250 years long series of observations made with meteorological instruments are available (e.g., MANLEY, 1958, 1961), however, there is plenty of evidence from observed temperatures to support the general indications of glacier recession etc. in establishing a noteworthy warming of world climates since about A.D. 1700. Statistically significant changes of temperature level have occurred even since 1880 (MITCHELL, 1963). And multifarious evidence of a meteorological nature from historical records, as well as archaeological, botanical and glaciological evidence in various parts of the world from the Arctic to New Zealand (e.g., KOCH, 1945; RAESIDE, 1948; MÜLLER, 1953; HOLLOWAY, 1954) has been found to suggest a warmer epoch lasting several centuries between about A.D. 900 or 1000 and about 1200 or 1300.

Both these climatic phases just referred to—some centuries respectively colder and warmer than the present day—were clearly fluctuations of shorter time-scale than the great post-glacial warm epoch of 5000 or 6000 to 3000 B.C., different from that probably in nature and causation. Even if some similar influences were operating in the lesser optimum around A.D. 1000, it is unlikely that *all* important elements of the much longer warm epoch were present. Nothing suggests that the warmth of the early medieval period attained that of the climatic optimum; though the cold period after A.D. 1550 probably did produce the lowest temperatures and the greatest extensions of ice on land and sea since the last ice age. It has often been called the "Little Ice Age" in consequence. Presumably because of their short duration, world sea level was hardly affected by either of these more or less extreme climatic phases of the last 1,000 years. In many ways therefore these are a lesser phenomenon than either the climatic optimum or an ice age (as usually meant): their time-scale is approximately that of the short-period fluctuations registered within the ice ages, including the post-Allerød recession between 9000 and 8000 B.C. Nevertheless, with this distinction in mind, they clearly merit investigation of the climatic values and world distribution of climates occurring and of the atmospheric circulation patterns required to produce them.

Palaeoclimatology is likely to be advanced by investigating first specific periods for which evidence that is sufficiently abundant and reliably dated indicates some well defined climatic character. It was for this reason that the "ad hoc Committee on Palaeoclimatology", formed in 1961 by the United States National Research Council, decided as its first act to hold a conference on the climates of the 11th and 16th centuries A.D., to be attended by active research workers in all relevant disciplines (ASPEN CONFERENCE, 1962).

Both the "Little Optimum" in the early Middle Ages and the cold epoch, now known to have reached its culminating stages between 1550 and 1700, can today be substantiated by enough data to repay meteorological investigation (see, for example, the preliminary treatment of both, given by LAMB, 1963a). The historical evidence is, of course, thinner for the earlier of these two epochs; nevertheless, it has been chosen for treatment here because the investigation is an interesting example of the pooling and interpretation of data from archaeology, botany, glaciology, human history, meteorology and oceanography. Moreover, there are potential practical applications to be got from an assessment of the warmest and coldest climatic phases of recent times. Something is already known of the temperatures, rainfalls and ice conditions in the latter part of the Little Ice Age directly from observations that are fairly readily available (see, for example, many titles in the bibliography at the end of this paper). The early medieval warm epoch poses rather more difficult problems of estimation, and one can detect the beginnings of doubt and controversy as to whether some purely descriptive accounts have overestimated its magnitude. On the other hand, all effects of climatic deterioration between about 1300 and 1600 upon the human economy in Europe, south of 60° N, have usually been attributed by historians (except, significantly, in Scandinavia) entirely to the Black Death and other disorders. It is high time therefore to marshal the climatic evidence and attempt a quantitative assessment.

GENERAL SURVEY OF EVIDENCE ON WORLD CLIMATES ABOUT 1000–1200 A.D.

Arctic

The Arctic pack ice was so much less extensive than in recent times that appearances of drift ice near Iceland and Greenland, south of 70° N, were apparently rare in the 10th century and unknown between 1020 and 1194, when a rapid increase of frequency caused a permanent change of shipping routes (KOCH, 1945). BROOKS (1949) suggested that the Arctic Ocean became ice-free in the summers of this epoch, as in the Climatic Optimum; but it seems more probable that there was some "permanent" ice, limited to areas north of 80° N. Evidence of early Norse burials in southwest Greenland, and plant roots deep in ground now permanently frozen, suggests that annual mean temperatures there must have been 2–4° C above present values. Sea temperatures in neighbouring parts of the North Atlantic were probably up by a similar amount. VEBAEK (1962, p.18) adds that by the 14th and 15th century the ground was permanently frozen close to the surface. CHARD and GIDDINGS (1962, p.17) deduce from archaeological evidence that the North American eskimoes (during the period of the Thule culture) first occupied Ellesmere Land about A.D. 900, and expanded their range northwest as far as the New Siberian Islands (75° N 140–150° E) and northeast around the north of Greenland; whaling and fishing were important to them and they used considerable amounts of driftwood for building. By the 16th century all this had ceased; Ellesmere Land and northern and northeastern Greenland were deserted, houses were smaller and there is less evidence of driftwood. There had been battles for the first time between the eskimoes moving south and the settlers in the old Viking colony in Greenland, which ultimately succumbed (STEFANSSON, 1943). Three studies by FRITTS (1962, p.21) in northern Alaska have indicated average summer temperatures there in the 11th century higher than the 1851–1950 average by a margin that may have been as much as 2.3° C.

Northern temperate lands

In central Norway the area of settlement, forest clearance and cultivation, which appears to have been more or less static since early iron age times, spread rather rapidly 100–200 m farther up the valleys and hillsides in the course of about two centuries from around A.D. 800; it retreated as decisively in the 14th century—partly owing to the Black Death, though the higher-level farms were left unoccupied for hundreds of years thereafter (HOLMSEN, 1961), and in some areas further farms were abandoned before the advancing glaciers as late as 1743 (HOEL and WERENSKIOLD, 1962). (There had, however, been an intermediate recovery of some economic importance about 1500 or in the 16th century.)

In central Europe, before some time which has been variously placed between 1300 and 1450, vineyards were cultivated farther north and up to 220 m higher above sea level than at present. The upper limit of forests in the Alps and more northerly ranges of hills in central Europe is estimated to have lain 70–200 m above the present limit (GAMS, 1937; FIRBAS and LOSERT, 1949) until a rapid decline occurred some time between 1300 and 1600. These differences indicate summer temperatures about 1° C or rather more above present levels (see Table III, later).

Archaeological evidence from the western Great Plains, the upper Mississippi valley and the arid southwest of the United States indicates a moister regime giving enough rainfall to support small agricultural settlements that were progressively abandoned from about 1250 onwards (GRIFFIN, 1961; ASPEN CONFERENCE, 1962, pp. 18–19).

By the 15th or 16th century tree studies suggest marked drought on the Plains; wind-blown deposits (dry westerlies?) overlaid the humus of the earlier period there.

Other latitudes

As regards lower latitudes, BROOKS (1949, pp.327, 355) indicated the early Middle Ages as a wet period in central America (Yucatan) and probably in Indo-China (Cambodia) and a relatively moister period in the Sahara from 1200 or earlier to perhaps 1550. BUTZER (1958, p.12) cites evidence of greater rainfall and larger rivers in the Mediterranean and Near East; some of this evidence comes from the descriptions of the Arab geographer Idris about the middle of the 12th century.

Sparser evidence from the southern hemisphere, including Patagonia, New Zealand and Antarctica (LAMB 1963a, p.128) indicates a variation similar to corresponding latitudes in the northern hemisphere. RAESIDE (1948) has estimated from soil studies that in New Zealand the climate between about A.D. 700 and 1300 was moist enough for forests on the downlands of Canterbury and parts of Otago and that average temperatures were "at least 2°C" higher than today's. A similar result appears to be indicated by HOLLOWAY's (1954) studies of changes in the distribution of tree species in the existing forests of South Island.

World Summary

The commonest indications from very diverse types of evidence are that prevailing temperatures in many parts of the world at least between 1000 and 1200, and possibly over a rather longer period, were about 1–2° above present values, though probably less in latitudes under about 40° where increased moisture and precipitation is the main indication. The temperature anomaly was evidently bigger, probably 4°C in places, near the coast of Greenland and possibly elsewhere along the rim of the Arctic Ocean. That the greatest anomalies should be there is not surprising, since very big differences of average temperature should occur at places which in one epoch are within the main region of permanently ice-covered surface or very near its edge and in another epoch, due to withdrawal or melting of the ice, are for much of the year outside this region. A 20th century parallel is provided by Spitsbergen, where the average annual mean temperature for the 1930–1940 decade wasal most 4°C higher than for 1912 – 1920, with corresponding rises of 1.5–2°C in Iceland and on the southeastern and southwestern coasts of Greenland (at Angmagssalik and Godthaab).

METEOROLOGICAL INVESTIGATION OF THE PERIOD ABOUT 1000–1200

Circulation of the atmosphere

Fundamentals

The first meteorological attempts at interpretation of climatic changes as a global phenomenon rested chiefly upon analogy with the observed regular features of seasonal change, especially the intensification of the winds and pressure differences from summer to winter and displacement equatorwards of the main depression tracks as the area of snow and ice around the polar region expanded. The most noteworthy example of this reasoning was SIMPSON's (1934) schematic reconstruction of the prevailing pressure and wind distribution in the ice age, which has, however, been subsequently amended by the present writer (LAMB, 1961).

Meteorology was hardly in a position to contribute to knowledge and understanding of former climates and climatic distributions until the invention of the radio-sonde about 1930 made possible a regular, so-to-speak continuous, survey of the large-scale flow of the atmosphere in depth. The world-wide network of observation has really only developed since 1945. This led to the discovery that the main flow consists of a rather simple vortex of upper westerly winds circulating in the zone of strongest thermal gradient over middle latitudes, girdling each hemisphere. These winds prevail over a broad range of latitudes between heights of 2 and 15–20 km; in middle latitudes the region of their dominance starts from the surface. Their flow is "thrown" into a system of waves (successive ridges and troughs around the hemisphere) by the major mountain barriers and thermal inequalities in middle latitudes. The wave length, or spacing between successive ridges and troughs, depends upon the dynamics of the flow, increasing when the windstream strengthens or is displaced towards higher latitudes.

The wave length (trough-to-trough or ridge-to-ridge, spacing) for stationary waves in a meandering windstream around the globe is expressed in degrees of longitude by L in the equation, due to ROSSBY (1939):

$$U = \frac{\beta L^2}{4\pi^2}$$

where U is the zonal velocity of the west-wind stream and β is $(d/d\Phi)$ $(2\omega \sin\Phi)$, in which Φ is the latitude and ω the angular velocity of rotation of the earth. These long waves and their changes of position, that accompany changes of wave length downstream from some more or less fixed ("anchored") disturbance due to the (physical or thermal) geography of the earth, appear to explain the shifts observed in the average positions of the main "centres of action" of the general wind circulation (surface high and low-pressure regions), as originally pointed out by ROSSBY (loc. cit.) in relation to their wanderings from week to week.

Investigation

Europe between about 45 and 55° N, from Ireland to Russia, is a region for which abundant manuscript information on the character of particular months and seasons exists, especially those of any sort of dramatic character, from early historical times. The records occur as allusions in state, local, monastic, manorial and family accounts and chronicles and in personal diaries. This region is also continually under the interplay of the surface weather systems, depressions and anticyclones, associated with the troughs and ridges in the main upper west-wind flow in the northern hemisphere circumpolar vortex. It is therefore an ideal region for study of long-term shifts of the "centres of action" of the atmospheric circulation associated with climatic changes. The waves in the upper westerly flow downstream from the Rocky Mountains disturbance should expand and be displaced eastwards over the Atlantic sector and Europe, together with the average positions of surface low and high pressure and corresponding surface weather anomalies, when the gradients strengthen or when the tropical warm-air regime spreads somewhat towards higher latitudes; they should, of course, undergo reverse movements when the opposite happens. An analysis of the incidence of reported good and bad weather anomalies in different longitudes across Europe may, in this way, tell us something of value about the general wind circulation.

Indices of relative frequencies of reported dry and wet summer months, mild and cold winter months were chosen for analysis (LAMB and JOHNSON, 1961; LAMB, 1963b).

Compilations by HENNIG (1904), VANDERLINDEN (1924), EASTON (1928), BRITTON (1937), MÜLLER (1953), BUCHINSKY (1957) and Dr. D. J. Schove (personal communication) of the original reports were used; and note was taken of BETIN and PREOBAZENSKY's (1959) long series of figures for the Baltic ice. As a first attempt to submit this material to meteorological analysis, the frequencies of markedly wet or dry summer months and of notably mild or severe winter months were studied in relation to their geographical distribution across Europe decade after decade.

The most reliable surface weather indications in the early manuscripts to use were thought to be:

(*1*) Mildness or severity of the weather prevailing in December, January and February. The effects upon landscape, transport and agriculture are likely to have been reported in all important cases. It should be possible to identify confidently the persistent spells: mild winters by rains, flooding and thunderstorms even in continental regions, also by early or out-of-season flowering of plants; severe winters by frozen waterways and by many sorts of privation and damage.

(*2*) Raininess or drought in July and August. Again the effects upon the landscape and upon agriculture are likely to have achieved mention in all important cases. Wet summers produce flooding and ruined crops, though highly coloured accounts of individual thunderstorms may occur in otherwise good summers. Dry summers are known by parched ground and dwindling rivers, whilst the grain crops are usually good; forest fires are also particularly liable to occur. The rain character of a summer is surer of faithful recording than the temperature, since one oppressive heat wave might well be the only recorded reference to temperature in an otherwise poor summer.

The numerical indices defined were applied to the years in groups of not less than a decade to eliminate the effects of uncertainties in early times regarding the exact year of a particular occurrence. Data for some groups of years appear full and self-consistent from quite early times,—e.g., the remarkable warmth and dryness of central European summers between A.D. 988 and 1000—but a complete sequence of characteristics of the individual decades can hardly begin before A.D. 1100. So as not to make too great demands in terms of uniform standards of reporting, the excess of mild or cold, wet or dry months was transformed into half-century means of the following indices, and the series was in this form tentatively extended back to A.D. 800:

(*a*) Winter mildness or severity index—the excess number of unmistakably mild or cold winter months (December, January, February only) over months of unmistakably opposite character per decade—excess of cold months counted negative. (Unremarkable decades score about 0. Extreme decade values of the index in Europe range from about +10 to −20.)

(*b*) Summer wetness index—each month (July and August only) with material evidence of drought counted 0, unremarkable months ½, months with material evidence of frequent rains and wetness counted 1. (Unremarkable decades score about 10. Extreme decade values of the index in Europe range from about 4 to 17.)

The results of analysis of the course of these indices over Europe since 800, depicted in Fig.1, do show the kind of eastward and westward movements across the continent of concentrations of wet and dry, warm and cold months, that have been demonstrated by the writer (LAMB, 1963b) in the case of trough and ridge regions (i.e., regions of low and high average pressure respectively) over the Atlantic and Europe at 45–55 °N in the Januarys and Julys since 1800. Moreover, in the period since 1800 both movements agree. The movements indicated for the summers and winters from the early Middle Ages are also broadly parallel. Measurement of the longitude displacements reveals that they are so large that, to explain them by the Rossby formula, we have to suppose that the mainstream of the wind circulation (the upper westerly winds) became both weaker and displaced south from 1300 to 1550 or 1600 and later largely recovered again, starting from 1700 to the present century. A prevailing warm epoch with dry anticyclonic character, especially in summer, in temperate Europe between about 1000 and 1300 A.D. appears to be confirmed.

Judged by the implied shift of the upper westerlies, the main depression tracks and the zone of low pressure associated with them (the "Iceland low") should have had, in the period 1000–1300, an average position 1–3° north of the

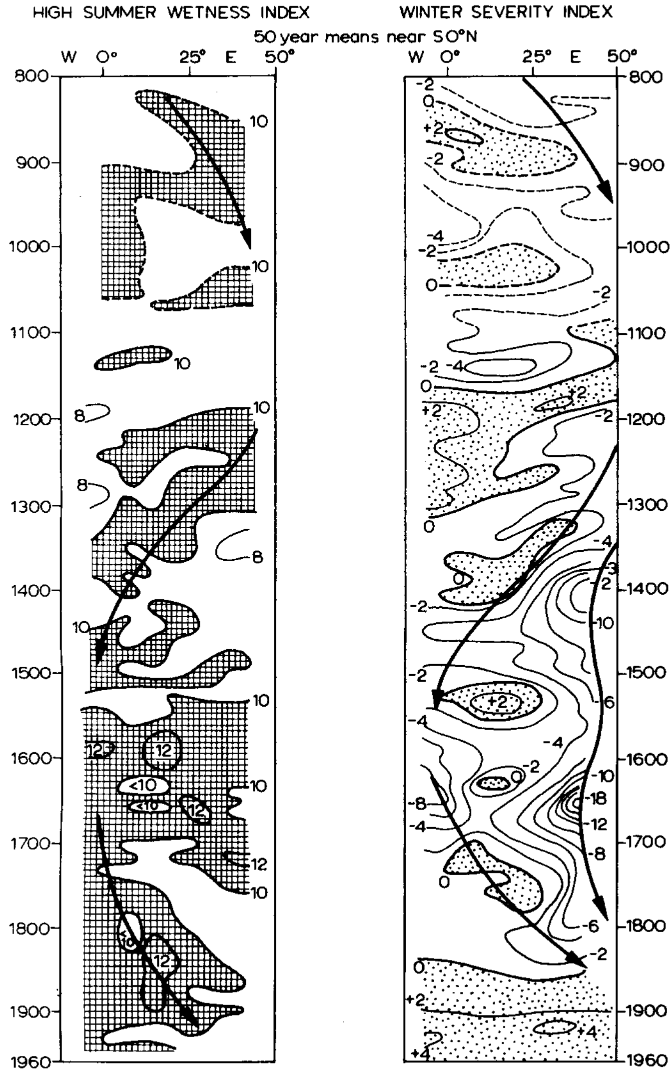

Fig.1. Summer dryness/wetness and winter mildness/severity indices in different European longitudes near 50°N, from 800 to 1959, overlapping half-century means. Cross hatching indicates excess of wet Julys and Augusts. Dots indicate excess of mild Decembers, Januarys and Februarys. The definitions of the indices are as follows: winter mildness/severity index—the excess number of unmistakably mild or cold winter months (D, J, F only) over months of unmistakably opposite character per decade—excess of cold months counted negative. (Unremarkable decades score about 0. Extreme decade values of the index in Europe range from about +10 to −20.) Summer dryness/wetness index—each month (July and August only) with material evidence of drought counted 0, unremarkable months 1/2, months with material evidence of frequent rains and wetness counted 1. (Unremarkable decades score about 10. Extreme decade values of the index in Europe range from about 4 to 17.)

modern normal (1900–1939 average) position— a displacement that probably implies less ice on the Arctic seas, because a northward progression by almost this amount between 1800 and 1940 went hand in hand with a roughly equal retreat of the ice.

Temperatures and rainfalls in England and neighbourings lands

Fig.2 displays the course of the summer and winter indices over England, indicating the frequencies of wet or dry summer months (Julys and Augusts), and mild or cold winter months, each decade since 1100. These graphs tell very much the story expected from the general evidence already cited. But it would be useful to discover, by statistical comparisons with the temperatures and rainfalls observed since about 1700, what average values of temperature and rainfall these (frequency) indices imply. This is attempted in what follows. It is important, however, to establish margins of error, and when these cannot be given, or are too wide, one must avoid premature commitment to the temperature or rainfall estimates, pending further evidence.

BERGTHORSSON (1962, pp.46, 51) has already computed average annual temperatures for Iceland for every decade since A.D. 940 using a straightforward, and apparently strong, statistical relationship between air temperatures in that country and the frequency of sea ice reported near the coasts of Iceland. The results indicate a prolonged warm epoch, lasting more or less from the beginning of the series to 1190 and reaching its height between 1100 and 1150; but, surprisingly, the indicated temperature level for 1100–1150 was only 0.4 °C above the 1901–1930 average and

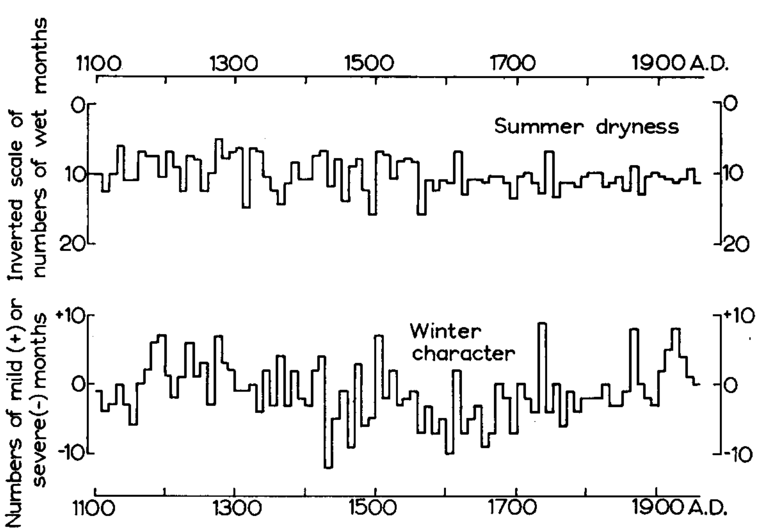

Fig.2. Values of the indices of summer dryness/wetness and winter mildness/severity in England for each decade 1100–1959. The definitions of the indices are as in Fig.1.

actually half a degree lower than that of the warmest recent decade, the 1930–1940 one. It is hard to reconcile this result with the evidence of conditions in south Greenland cited in the previous section; and it must be suspected that the statistical relationship cannot be used in decades when the ice has retreated altogether from the area. The investigator made some reference to this very difficulty as applying to the warmest decades of the present century. Much of Bergthorsson's series is nevertheless of undoubted value. In the decades when sea ice was present and caused varying degrees of trouble, the temperature values are likely to be mostly reliable; they probably therefore give a more detailed sequence over a longer period of years than will be possible for any other country.

Correlation coefficients connecting the summer wetness and winter mildness or severity index values with rainfall averages over England and Wales (NICHOLAS and GLASSPOOLE, 1931) and with temperatures in central England (MANLEY, 1958, 1961) for the decades since about 1700 were found to be as listed in Table I.

The rainfall values before 1740 were not used because of some doubts about exposure and adequacy of the few reporting gauges in the earliest years. The figures reported for the 1730–1740 decade appear too low in relation to what is known of the wind circulation patterns occurring in that decade. Nevertheless, some tendency to dryness can be accepted, partly because of the probability of low

TABLE I

CORRELATION COEFFICIENTS BETWEEN DECADE VALUES OF TEMPERATURE AND RAINFALL AND RELATED INDICES

	r	*Standard error*
High summer (July and August) rainfall (R_{JA}) vs. summer wetness index (w) since 1740	+0.91	±0.04
Winter temperature (T_{DJF}) vs. winter mildness index (m) since 1680	+0.87	±0.05
High summer temperature (T_{JA}) vs. summer wetness index (w) since 1680	−0.23	±0.18
Annual mean temperature (T_y) vs. arithmetic mean of high summer and winter temperatures $^1/_2(T_{JA}+T_{DJF})$ since 1680	+0.89	±0.04
Annual rainfall (R_y) vs. high summer rainfall (R_{JA}) since 1740	+0.09	±0.21
Annual rainfall (R_y) vs. annual mean temperature (T_y) since 1740	+0.42	±0.18
10 months rainfall (September–June) (R_{10}) vs. winter temperature (T_{DJF}) since 1740	+0.65	±0.12

TABLE II

PREVAILING TEMPERATURES (°C) IN CENTRAL ENGLAND AND RAINFALLS (% OF 1916–1950 AVERAGES) IN ENGLAND AND WALES

Period	*Temperatures*[1]				
	Winter (DJF)	*Winter (DJF) adjusted for probable under-reporting of mild winters in medieval times (see text, see also notes above)*	*High summer (JA)*	*High summer (JA) Adjusted to meet certain botanical considerations (see text)*	*Year, based on the adjusted values given for winter and summer*
800–1000	3.5	3.5	15.9	15.9	9.2
1000–1100	3.7	3.7	(16.2)	16.2	9.4
1100–1150	3.5	3.5	(16.2)	16.5	9.6
1150–1200	3.9	4.2	(16.3)	16.7	10.2
1200–1250	3.8	4.1	(16.3)	16.7	10.1
1250–1300	3.9	4.2	(16.3)	16.7	10.2
1300–1350	3.6	3.8	15.9	16.2	9.8
1350–1400	3.6	3.8	15.7	15.9	9.5
1400–1450	3.4	3.4	15.8	15.8	9.1
1450–1500	3.5	3.5	15.6	15.6	9.0
1500–1550	3.8	3.8	15.9	15.9	9.3
1550–1600	3.2	3.2	(15.3)	15.3	8.8
1600–1650	3.2	3.2	(15.4)	15.4	8.8
1650–1700[3]	3.1	3.1	(15.3)	15.3	8.7
1700–1750[3]	3.7	3.7	15.9	15.9	9.24
1750–1800	3.4	3.4	15.9	15.9	9.06
1800–1850	3.5	3.5	15.6	15.6	9.12
1850–1900	3.8	3.8	15.7	15.7	9.12
1900–1950	4.2	4.2	15.8	15.8	9.41

[1] Temperatures from 1680 averages taken from MANLEY's (1958, 1961) homogenized records. Temperatures before 1680 averages derived from decade values of the winter mildness/severity index and the summer wetness/dryness index (p.20) using regression equations based on comparisons with observed values since 1680–1740 (see text). Bracketed values have been adjusted for systematic departures from the regression line indicated by wind circulation characteristics. A separate column gives winter values adjusted on other meteorological considerations explained in the text, so that the mildest decades between 1150 and 1300 have temperatures equalling those of the 1920–1940 period. The balance of all the evidence meteorological and non-meteorological appears, however, to favour the still higher values indicated by the thin line in Fig.4. Summer temperatures adjusted to fit certain botanical indications are given in a separate column.
[2] Rainfalls from 1740 averages taken from NICHOLAS and GLASSPOOLE (1931) and Meteorological Office records. Rainfalls before 1740 averages derived from decade values of the summer wetness/dryness index and from the adjusted average values of annual mean and winter temperature, as explained in the text, using regression equations.
[3] Values given for the temperatures 1650–1700 and rainfalls 1700–1750 incorporate instrument measurements for part of the period and the margins of error (as indicated in Fig.4 and 5) are reduced in consequence.

TABLE II *(continued)*

Year	*Rainfalls*[2]		*High summer rain as % of the year's rain*	*Period*
	High summer (JA)	*September to June*		
96	93	97	17	800–1000
97– 98	94	98	17	1000–1100
98–100	93	102	17	1100–1150
100–106	86	107	15	1150–1200
100–104	86	105	15	1200–1250
100–106	84	107	14	1250–1300
98–101	89	102	16	1300–1350
97– 98	105	96	19	1350–1400
95	88	97	16	1400–1450
95	106	93	20	1450–1500
97	84	99	15	1500–1550
93– 94	106	91	20	1550–1600
93– 94	99	92	19	1600–1650
92– 93	104	90	20	1650–1700[3]
96– 97	92	98	17	1700–1750[3]
94	109	91	21	1750–1800
96	97	96	18	1800–1850
97	98	97	18	1850–1900
99	97	100	17	1900–1950

sea temperatures left over from previous cold decades and consequently rather low atmospheric moisture content.

The relationships listed in the table can be used to form regression equations to derive half-century or longer-period mean values of temperature and rainfall in England from the summer and winter indices; but two of the correlation coefficients are too low to use, and in some cases corrections were indicated by critical consideration of the figures in relation to all the known evidence. Where no such corrections are required it is possible to quote margins of error that are thought strictly reliable. The results are given in Table II and in Fig. 3, 4 and 5, the error margins quoted being 99% confidence limits (3σ). To derive these results, decade values and half-century means of all the parameters compared in Table I were plotted against one another (not illustrated); the individual cases were then

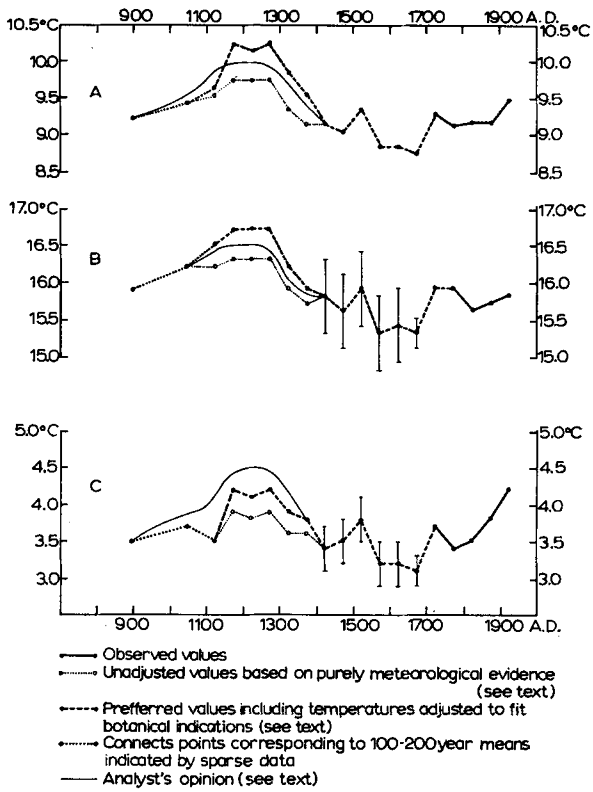

Fig.3. Temperatures (°C) prevailing in central England, 50-year averages. A: year; B: high summer (July and August), and C: winter (December, January and February). Observed values (as standardized by MANLEY, 1958, 1961) from 1680. Values for earlier periods derived as described in the text. The ranges indicated by vertical bars are three times the standard error of the estimates.

examined in relation to their departures from lines representing the regression equations and in relation to what is known of the meteorology of each decade since 1680 (particularly the prevailing January and July circulation patterns) (LAMB 1963a,b).

The average winter temperatures[1] in the second column of Table II and the July and August rainfall values were derived in this straightforward manner[2]. The July–August rainfalls may be satisfactory without any adjustment and are

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[1] The regression equation for decade averages of winter (Dec., Jan. and Feb.) mean temperature (T_{DJF}) in central England on winter mildness/severity index value (m) is: $T_{DJF} = 3.69 + 0.11m$ in °C. The standard error of the estimates that result appears to be 0.25°C (but see corrections discussed later in the text).

[2] The regression equation for decade values of July and August rainfall (as % of the 1916–1950 average) over England and Wales (R_{JA}) on the summer wetness index value (W) is: $R_{JA} = 6.52W + 29.1$. The standard error of the resulting percentage figure appears to be $\pm$ 4.01.

believed to be reliable within the margins of error indicated in Fig.4 from 1350. Summers of the period 1150–1300 must have been drier than in subsequent centuries because of the much lower values of the wetness index; it remains possible, however, that some upward adjustment should be applied, since prevalence of higher air and sea temperatures would probably give heavier rain in thunderstorms. The figure for the summers of 1300–1350 may be too low because it contains no adjustment for a run of very wet years between 1316 and 1320.

In the case of winter temperature, it is likely that some adjustment is needed over the whole period before about 1400. This is because the circulation characteristics deduced by wave-length arguments (cf. p.20) from Fig.1, as well as the indications from the state of the Arctic ice and from Greenland (p.16) that ocean temperatures were at least as high as those of today, and probably rather higher, make it unlikely that the winter temperatures prevailing in the warmest decades of the 12th, 13th and 14th centuries were any lower than those in the warmest decades of this century (the 1920–1930 and 1930–1940 decade). Moreover westerly winds are known to have been at times very prevalent in England, particularly around 1340. Despite the abundance of reports of the nature of the seasons in Europe from those early years, one is driven therefore to suspect that winters which would nowadays be considered mild did not always achieve mention and that this has affected the winter mildness index values slightly before about 1400. The "adjusted" values of winter temperature in the third column of Table II have been raised on these grounds just enough to bring the highest average values in the period 1150–1300 up to the same level as those of 1900–1950. The further stages of this investigation, however, raise the suspicion (not altogether surprisingly) that the average winter temperatures of that early period should be even a few tenths of a degree higher (e.g., the reference to sea temperatures on p.33). This argument does not altogether apply between 1000 and 1150 when such high latitudes are indicated for the main depression tracks that the winters in temperate Europe were presumably rather anticyclonic and continental air would be not infrequent in the British Isles. At the same time, the known diminution of the Arctic sea ice probably meant that Arctic airmasses over the continent were somewhat less cold than nowadays.

The correlation coefficient between high summer temperatures and the summer wetness index (Table I) is not high enough to proceed upon. (Deduced temperature values would have too wide a margin of error.) Examination of the relationship in individual decades since 1690 reveals, however, that the large departures from the regression line[1] (groups of four to six outstanding decades above

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[1] The regression equation for decade values of high summer (July–August) average temperature (T_{JA}) in °C in central England on summer wetness index value (W) is: $T_{JA} = 16.40 - 0.062W$. The standard error of the estimates derived appears to be 0.36°C—too wide a margin for the estimates to be usable without the further adjustments and considerations discussed hereafter in the text.

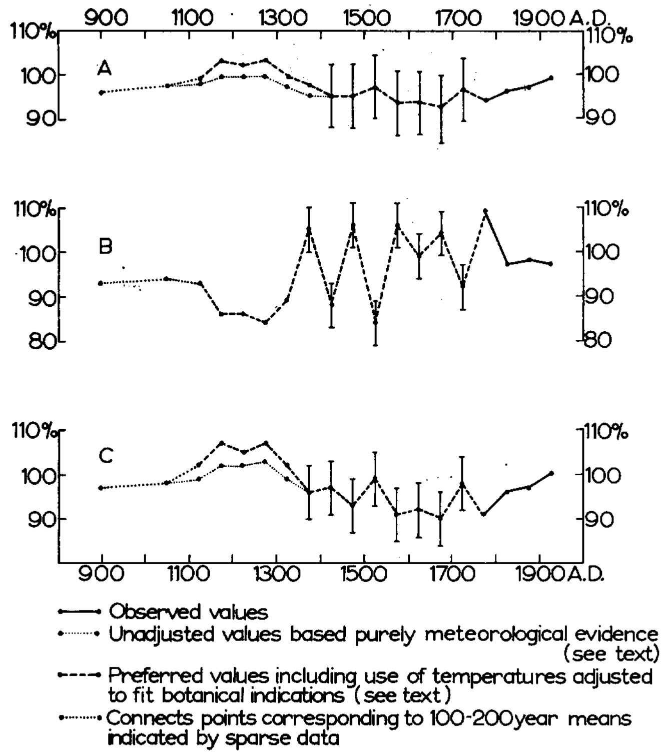


Fig.4. Rainfall amounts (as % of the 1916–1950 averages) over England and Wales, 50-year averages. A: year; B: high summer (July and August), and C: cooler 10 months of the year (September–June). Observed values (as presented by NICHOLAS and GLASSPOOLE, 1931) from 1740. Values for earlier periods derived as described in the text. The ranges indicated by vertical bars are three times the standard error of the estimates.

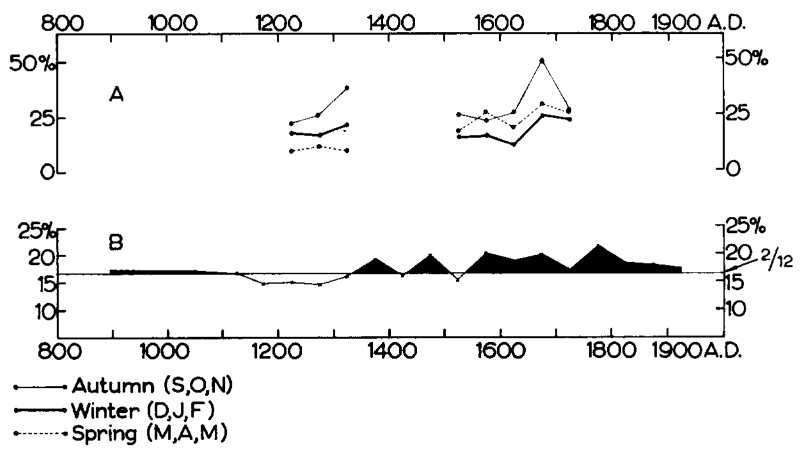


Fig.5. Seasonal rainfall characteristics deduced for England and Wales. A: frequency (%) of months described as wet in autumn, winter and spring. (Snowy months have not been included in the counts, because the equivalent rainfall is nearly always below normal. Data insufficient before 1200 and between 1350 and 1500.) B: percentage of the year's total rainfall falling in July and August. (Shaded area indicates excess over the proportion due for $^2/_{12}$ of the year.)

and below the line) appear to be systematic and such that the decades with pronounced anticyclonic tendency or southerly wind component over the British Isles all gave values about 0.4 °C above the regression line, whereas those with pronounced cyclonic character or northerly wind component averaged 0.4 °C below the regression line. This difficulty is an inevitable consequence of choosing a wetness index as more reliable to represent the summers than any available reports of temperature. The figures for average temperatures in high summer in the fourth column of Table II are based upon the regression line with corrections applied (+0.4 °C) for the deduced anticyclonic tendency between 1100 and 1300 and (−0.4 °C) for the known tendency for cyclonic character and rather frequent northerly wind components between 1550 and 1700. (The latter case was partly verified by the evidence of thermometric observations in the period between 1680 and 1700, which also reduce the error margin of the average for 1650–1700 in Fig. 3.)

All the values so far referred to in Table II and Fig.3 and 4 have been arrived at by purely meteorological evidence and may be regarded, subject to the caution mentioned about winter temperatures, as the most probable values indicated by that evidence considered alone.

Botanical evidence, however, suggests still higher summer temperatures in the early Middle Ages leading to the values given in the fifth column of Table II. These are explained by the items listed in Table III, in which temperature changes

TABLE III

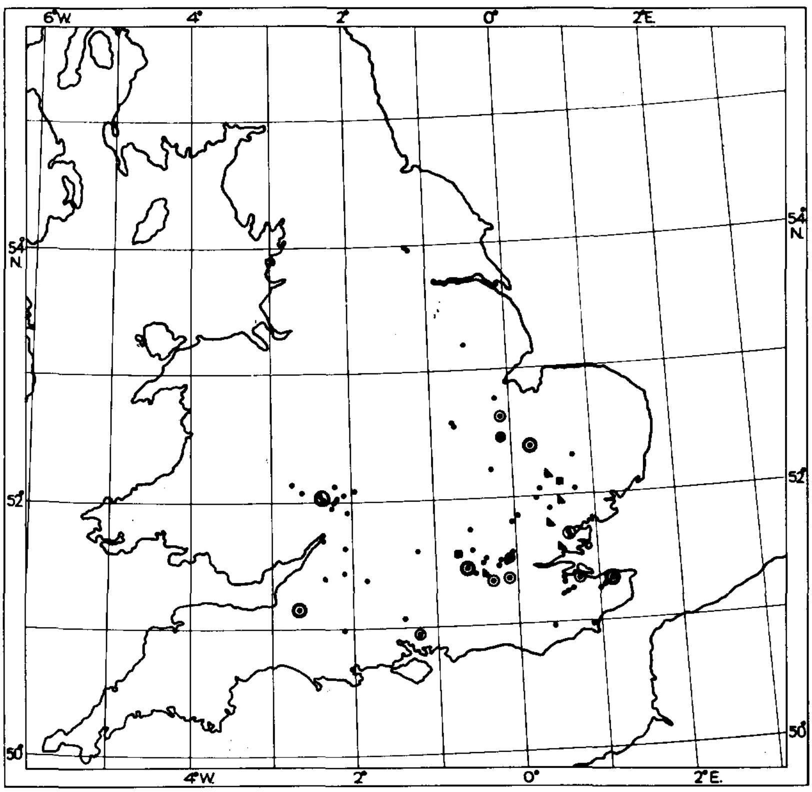
ANOMALIES CIRCA 1150–1300 BY REFERENCE TO THE AVERAGE VALUES ABOUT 1900 OF MEAN TEMPERATURE OF THE WARMEST MONTH INDICATED BY BOTANICAL AND VITICULTURAL EVIDENCE

Lowering of the upper tree limit in the Vosges, Black Forest and Sudetenland by 100–200 m, between 1300 and 1500 A.D. (FIRBAS and LOSERT, 1949)	+0.7–1.4 °C
Lowering of the upper tree limit on Monte Rosa and in the Swiss Alps (Valais) after 1300 (GAMS, 1937) by 70 m	+0.5 °C
Lowering of the upper limit of cultivation of fruit and grain crops in the mountain districts of central Europe after 1300 (GAMS, 1937)	No figure given
Lowering of the upper limit of vineyards in southwestern Germany (Baden) by 220 m after 1300–1430 (MÜLLER, 1953)	+1.5–1.6 °C
Retardation by 20 days to middle October of the average date of grape picking in the Vivarais district (45.7°N 4.8°E) near Lyon between about 1550 and 1800 (ARAGO, 1858). calculated to give the same number of degree days above the 6 °C threshold marking the beginning of the growing season in early March	+1.0 °C[1]

[1] It is likely that some additional lowering of summer temperatures had taken place before 1550, though this might be offset by the recovery since 1800.

corresponding to height changes of the upper tree limit etc. on the continent have been reckoned in accordance with the present observed mean lapse rate in July over central Europe, at the relevant heights, of 0.7 °C per 100 m.

These considerations suggest that the evidence of the English medieval vineyards should be given such weight as it plainly suggests. The distribution of these vineyards, with their size and continuity of cultivation as indicators of success may be seen in Fig.6 and compared with the modern limits of vine growing, shown in Fig.7. There had been vineyards, which were well thought of, in England from earlier Saxon times; of the status of the few Roman vineyards established after A.D. 280 we have no knowledge. Success in the period 1100–1300, or possibly



LEGEND

- Vineyard, usually 1–2 acres or size not known.
- Vineyard, 5–10 acres.
- Vineyard, over 10 acres.
- O Denotes evidence of continuous operation for 30–100 years.
- O Denotes evidence of continuous operation for over 100 years.

Fig.6. English vineyards recorded between A.D. 1000 and 1300. Sources: CAMDEN, 1586; ELLIS, 1833; SIMOM, 1946; DARBY, 1952; HYAMS, 1953; ORDISH, 1953.

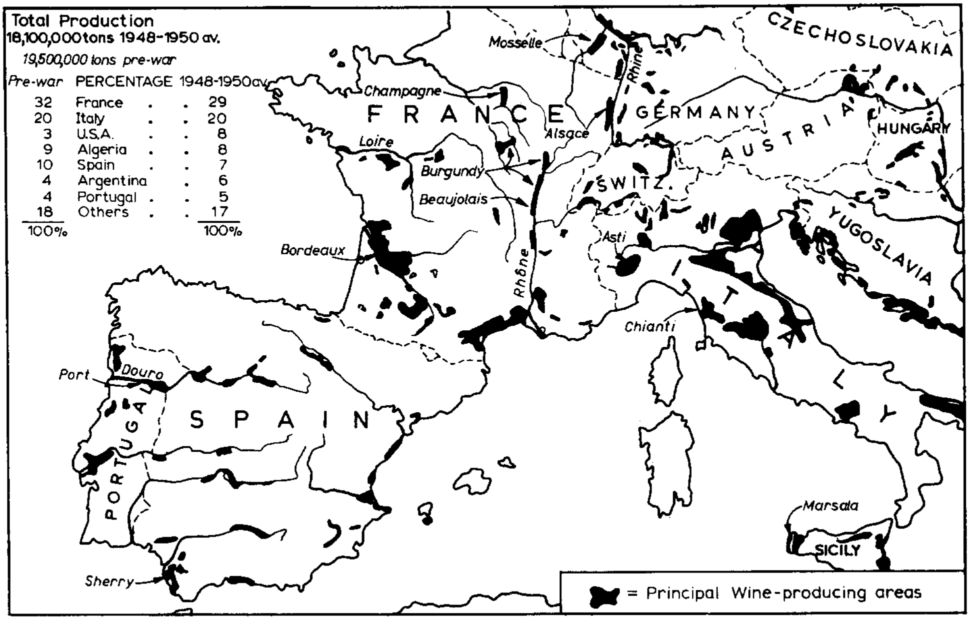


Fig.7. Distribution of modern commercial vineyards in Europe, from *The Oxford Economic Atlas* (1954). (Courtesy Clarendon Press.)

even a little later, was such that the French trade sought to have them abolished by an early treaty of peace with England (ELLIS, 1833). From William of Malmesbury's description about 1150 of the vineyards in the Vale of Gloucester and at Thorney near Peterborough it appears that these were open vineyards, not protected by walls.

For a good grape harvest the vine makes the following climatic demands: (*1*) freedom from late spring frosts, especially at and after flowering, (*2*) sufficient sunshine and warmth in summer, (*3*) not too much rain, (*4*) sufficient autumn sunshine and warmth, in regions where the summer is only just warm enough, to raise the sugar content, and (*5*) a dormant winter season, in which frosts are seldom serious.

Severe frosts have affected the northern limit of vineyards in France and Germany in a few of the most historic winters—cultivation was never resumed in some parts of France after 1709, and the winters of the 1430–1440 decade may have had a similar outcome both in France and Germany. Probably a prolonged period of frost and extreme temperatures below −20 to −25 °C are required for this to happen. Such temperatures have occurred in some of the former English vine districts but it seems likely that (with the possible exception of Ely in the 1430–1440 decade) such frosts only occurred after cultivation had already ceased. Severe frosts are less likely to have been the limiting factor at any stage of the climatic decline in England than on the continent. The figures in Table IV and V suggest that it was

TABLE IV

TEMPERATURES (°C) REPRESENTING THE MODERN NORTHERN LIMIT OF COMMERCIAL VINEYARDS

	Average lowest in May	*Extreme lowest in May*	*Average temperature of July*	*Average temperature of October*
Reims (1891–1956)	+0.5	−2.2	18.9	10.3
Luxemburg (1854-1956)	+1.7	−3.3	18.1	9.7
Köln (1851–1930)	+3.3	−0.5	18.6	10.5
Frankfurt/Main (1851–1936)	+2.8	−1.0	18.6	9.7
Apparent lowest acceptable values (approx.)	+1.0	−2.0	18.0	10.0

TABLE V

SHORTFALL OF PREVAILING TEMPERATURES (°C) IN 1921–1950, BELOW THE VALUES IN THE BOTTOM LINE OF TABLE IV, IN WHAT WERE IN 1150–1300 BY REPORT THE BEST ENGLISH WINE DISTRICTS

District and station used	*Average lowest in May*	*Extreme lowest in May*	*Average for July*	*Average for October*
Fenland (Cambridge)	1.5	2.5	1.0	0
Hereford–Gloucester border (Ross)	0.5	0.8	1.3	0
Middle-lower Severn and Thames valleys (Oxford)	0.5	0	1.0	0
London (Greenwich)[1]	0	0.2	0.2	0
Mid Essex valleys (Halstead)	1.5	1.9	0.7	0
Kent (Canterbury)[2]	0.1	1.9	0.6	0

[1] Greenwich temperatures may be raised slightly by the artificial climate of the built-up area of London.
[2] Canterbury data 1921–1944 only.

cool springs, May frosts and to a less degree lack of summer warmth that in the end told against the vine in England.

Tables IV gives relevant climatic values near the modern northern limit of commercial vineyards, and Table V indicates how far 20th century temperatures in the best of the former English vine districts appear to fall short of the lowest values required. (It is true that individual enthusiasm has succeeded in operating, often, but not always, in walled gardens, isolated vineyards in specially favourable sites in the south of England at one time or another in most centuries since the Middle Ages, though these have never continued long after the retirement or death of the founder.)

On the strength of the figures in Table III and V the July–August average temperatures at the peak of the medieval warm epoch in the fifth column of Table II have been adjusted to values 0.8 °C above those indicated by the regression equation (0.9 °C above the 1900–1950 average). These values are represented by the bold printed graphs in Fig.3. The sites of a number of the reportedly most luxuriant vineyards of the 12th and 13th centuries, particularly those at Tewkesbury, and in the Isle of Ely and the Essex valleys, probably require that May frosts either did not occur or were much rarer than in the present century. This seems to imply higher average sea temperatures around Britain than nowadays and, therefore, probably also milder winters.

The thin continuous curves in Fig.3 represent the analyst's recommendations, at the present stage, as the most probable course of the 50-year temperature average when account is taken of all aspects and all known shortcomings in the evidence. The departures between these curves and the bold lines in Fig.3 are small enough to imply no important differences in the rainfall figures derived from the regression equation. The slightly lower temperatures indicated for high summer do imply that climatic conditions in the medieval English vineyards were not fully equivalent to those of the northernmost commercial vineyards on the continent today, though the difference would be only a few tenths of a degree. It is noticeable, in Fig.6, that the longest-continued, and presumably most successfull, English vineyards were not the biggest ones: this may mean that specially careful management was always a factor in their success.

Using the summer and winter temperatures in the third and fifth columns of Table II, the appropriate regression equation[1] leads to the estimates of annual mean temperature in the sixth column.

The estimates of average yearly rainfall in Table II and Fig.4 are derived from the yearly mean temperatures given, and from the winter temperatures adjusted to be at their mildest in the medieval warm epoch the equal of the present century, using the appropriate regression equations[2]. These lead in some cases to alternative estimates which account for the ranges given. Any slight further raising of the winter temperatures on the grounds alluded to (p.33) would make no material difference to the derived rainfall values. Finally, the rainfall averages in Table II for the 10-month period that excludes the high summer, were given by the differences between the amounts of rain implied by the other two columns.

[1] The regression equation for decade values of yearly mean temperature in central England (T_Y) on the arithmetic mean (T'_m) of the winter (T_{DJF}) and high summer (T_{JA}) temperatures is: $T_Y = 0.864T'_m + 0.75$. The standard error of the estimates is 0.16 °C.

[2] The regression equation for decade values of average yearly rainfall in England and Wales (R_Y) as % of the 1916–1950 average rain on average yearly temperature T_Y is: $R_Y = 9.80\ T_Y + 6.2$. The standard error of the percentage estimates so derived appears to be 4.65. The corresponding regression equation for values of rainfall over the 10 months September–June (R_{10}) on winter temperature is: $R_{10} = 7.81\ T_{DJF} + 66.6$. The standard error of these estimates appears to be 4.29.

CONCLUSIONS

(*1*) The medieval warm epoch and the subsequent cold centuries, the so-called "Little Ice Age", are confirmed. The differences in the long-period temperature averages were, however, small enough—in England only 1 or (more probably) 1.2 – 1.4 °C, summer and winter, between these extreme epochs—to account for the impressions of some earlier meteorologists and workers in other disciplines that there have been no significant changes of climate in Britain or Europe since the beginning of the "sub-Atlantic period" around 500 B.C.

(*2*) Nevertheless this range of alteration of the average temperature level would be highly significant in statistical and meteorological terms, as well as in the implications for agriculture, transport in the wetter and colder seasons, and the human economy. It implies that within the last 1,000 years the climate of central England, considered over stretches of 50–150 years, has ranged in *summer* between the modern values for the extreme south of England and those for the Scottish border and in *winter* between modern values for Dublin (Ireland) and those for Holland between the coast and the Zuyderzee. The changes in the south of England are thought to account for the history of the vineyards, and the corresponding changes in central Norway would probably be sufficient to account for the drastic changes in the extent of land that was settled and farmed before and after the climax of the medieval warm period. There are indications that in Scotland the economy and character of community life were affected (LAMB, 1964). In Greenland, where the temperature anomaly appears to have been greater, and to a slightly less extent in Iceland, the climatic decline that followed was by itself sufficient to bring disaster to the whole community.

The range of variation of 50-year *average* summer temperature has apparently been of the same order as that of *average* winter temperature, but the range of temperatures characterizing the individual extreme winters exceeds that between the extreme summers. Probably of wider importance, however, are the variations implied in the length of the growing season and in the incidence of frosts that are prolonged and severe.

(*3*) Rainfall variations in England over the thousand years surveyed in Fig.4 have perhaps been more notable than those of temperature. Although annual rainfall was apparently lowest in the Little Ice Age period between 1550 and 1700, the difference as regards wetness of the ground was probably offset by less evaporation and wetter summers.

(*4*) There is evidence from bog stratigraphy in England and Ireland and in the Dutch, Danish, Swedish and northwest German lowlands of an important wet period between about 1200 and 1400 (e.g., GODWIN, 1956, p.34); and this is supported by frequencies of floods mentioned by BROOKS (1949) for England and BUCHINSKY (1963) for the Russian plain. This agrees reasonably with the high rainfall figures here derived, and especially their probable effect when temperature levels began to fall about 1300, reducing evaporation. The very wet character of the earliest stages of the climatic decline from 1200 or 1300 onwards is best explained by adopting the highest values of average winter air temperatures in England, and of implied ocean surface temperatures, hinted at in this account, i.e., mean winter temperatures in central England about 4.5 °C between 1150 and 1300, as indicated by a thin line in Fig.3.

(*5*) Changes are implied in the seasonal distribution of rainfall in England which also appear interesting (Fig.5). It is the relative contribution of the summers and winters to the year's rainfall which seems to have undergone the biggest changes. The medieval warm epoch appears as one of dry summers, i.e., an oceanic, summer-anticyclonic type of regime. In the subsequent cold epoch, and to some extent ever since, the summers have contributed a more than proportionate share of the year's rain, whereas the winters became relatively dry. Dryness of the winters is noted repeatedly in the 16th century records in England, about the time of the onset of most "continental" climate with increased frequency of freezing of the rivers.

Autumn is seen as having been always more prone to wetness than spring. The particularly high frequency of wet autumns around 1300–1350 and 1650–1700 was probably important in its effects on many things. The wetness of the autumns and winters, and over more limited runs of years the wetness of all seasons, appears as one of the most striking features of the climatic decline (i.e., period of cooling) at the end of the medieval warm epoch. It seems, from the high correlation coefficient found between winter temperature and rainfall in the cooler seasons (Table I), as well as on the physical arguments used with some apparent success in this investigation, to be linked with high sea temperatures and frequent westerly winds in a period of increasing cyclonic influence in England (i.e., of depressions passing nearer England than before). Botanical evidence of "recurrence surfaces", marking renewal of growth, in the peat bogs of northwestern Europe may point to this as a common characteristic of climatic periods that have ended warm epochs.

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