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COMPLEX DEMODULATION AND THE ESTIMATION OF THE CHANGING CONTINENTALITY OF EUROPE'S CLIMATE

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ABSTSACT

Six long records of European mean monthly temperature have been analysed for changes in continentality of climate using the time series technique of complex demodulation. Variations in amplitude and phase of the annual temperature cycle as estimated by the complex demodulation, in combination with low-pass filtering, are found to be coherent across much of Europe, from distinctly maritime to distinctly continental locations. The most significant departure of continentality found during the last 460 years is the maritime period of the 1920s when cool summers accompanied mild winters along with a retardation of the seasons throughout Europe.

KEY WORDS *Continentality* *Temperature* *Edinburgh* *Europe* *Complex demodulation*

INTRODUCTION

Detailed compilations of historical meteorological data, from land and sea, have been assembled by many groups. Much painstaking and exacting work has gone into cross-checking and systematically removing inhomogeneities and biases in the records, in accounting for the effects of any changes in the local exposure at observation sites and in identifying and setting aside stations with excessive warming trends caused by urban development. The resulting homogenized records form a remarkably detailed data base for palaeoclimatic studies.

Landsberg's (1985) very readable review summarizes the instrumentation and procedures of some early meteorological observers and describes changes in the types of information recorded in early weather diaries. Following the development of the thermometer in the seventeenth century, instrumental records of temperature have become progressively more continuous and widespread. The earliest observations that can be used as part of a continuous series stretching to the present day come from western Europe, in particular from England and The Netherlands. The main interest in historical instrumental temperature records has recently focused on the long-term changes of mean temperature, in the identification of periods of sustained warming or cooling and in their value in helping to assess future climate change. For example, it has been widely reported that global analyses of the temperature data for the last century have demonstrated a warming of the Earth of 0.5 °C (e.g. Jones and Wigley, 1990). The emphasis of this paper lies instead in analysing long instrumental records of mean air temperature for changes in the yearly range in temperature.

Many schemes of assessing the relative oceanicity or continentality of climate have been proposed, e.g. by Strahler and Gorczynski (Barry and Chorley, 1987) and by Driscoll and Yee Fong (1992). The great majority, however, explicitly or implicitly involve the yearly range of temperature. The yearly temperature range is usually incorporated into a continentality index by combination with latitudinal correction factor, e.g. Conrad (1946) and used to study spatial variations in continentality. Here it is the temporal changes in continentality, as caused by variation in the prevailing wind direction, or by changes in circulation of ocean currents, that are of interest and no latitudinal correction factor is needed. A procedure for determining a quantitative measure of the time–local annual temperature range might then be expected to reveal changes in continentality with time. Complex demodulation is a technique that can be applied to a time series in

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order to assess the variation, over time of the amplitude and phase of any selected frequency component. It is used here to extract long-term changes in annual temperature variation from instrument-based mean temperature time series. These changes in the yearly range in temperature, as derived by the complex demodulation, are then standardized and used as an index of continentality (large annual temperature change) as opposed to oceanicity (small annual temperature change) of the climate of north-west and central Europe during the past three centuries.

THE INSTRUMENTAL DATA

The longest record of mean monthly air temperatures is that constructed by Manley (1974) for central England. The series commences in January AD 1659. Manley (1974) describes the array of procedures he used to tackle the difficulties of standardization of the diverse records used in building up this exceptionally long time series. Parker *et al.* (1992) have formed a daily series based around the Manley monthly averages for the period AD 1772–1991. These particularly long English records are the result of a monumental amount of very careful work and diligent historical research. It seems unlikely that these carefully researched records will ever be substantially improved upon. Nevertheless one must be aware of many potential difficulties with them.

Elsaesser *et al.* (1986) have discussed problems with representativeness and homogeneity of historical observations of surface temperatures. They draw particular attention to changes in observing schedules and techniques over the time period of these long records. Manley made particularly careful adjustments, through the use of overlapping records, to compensate his monthly series for changes in instrumentation and observational procedure (Parker *et al.*, 1992). Some of the major differences that needed to be taken into account included (i) changes from indoor observations, in ventilated, unheated rooms, to outdoor observations, (ii) the advent of Glaisher stands, in the mid-nineteenth century, and (iii) the change to the present practice of exposure in a Stevenson screen. Careful adjustments were similarly necessary to correct for changes of observation time (e.g. from two or three daylight readings) to the now 'standardized' 1/2 (daily maximum + daily minimum). Manley again tackled these observational problems by his use of overlapping series. In addition to correction of the temperature data the time-scale of such long series also needs careful attention, for as Manley points out the calendrical months needed rectification from the Julian to the Gregorian calendar.

The second longest mean monthly air temperature series is the Utrecht record that was built up in The Netherlands by Labrijn (1945) and extended to the present day by Van Engelen and Nellestijn (1992). This excellent series begins in Delft in January AD 1706. Manley in fact had to draw on Labrijn's compilation to estimate central England temperatures for the one gap that occurs in the English data between AD 1707 and AD 1722.

By the mid-eighteenth century regular temperature measurements were being made in a number of European countries. An uninterrupted monthly sequence for Berlin commences in December AD 1755 (Schlaak, 1982). Two other long sequences are Stockholm, which starts in January AD 1756, and Uppsala, which begins in January AD 1774. All three of these sequences run through to the present day. Finally, Mossman (1897, 1900) had put together a series for Edinburgh beginning in January AD 1764 with the observations by Hoy at Hawkhill House. The Mossman series, for Edinburgh, has been extended to the present day using observations from the Nautical School, the Royal Observatory, and Turnhouse airport (author's unpublished calculations).

These six continuous mean monthly temperature series from Edinburgh, Central England, Utrecht, Berlin, Stockholm, and Uppsala were thus available for use in the complex demodulation study of the yearly range in temperature as described below (Figure 1).

DATA ANALYSIS

Homogeneity testing

As a first stage of data analysis the six series were examined for (i) any outliers and (ii) any discontinuities. Initially, time series (e.g. Figure 2) of the temperature data were plotted for visual examination and

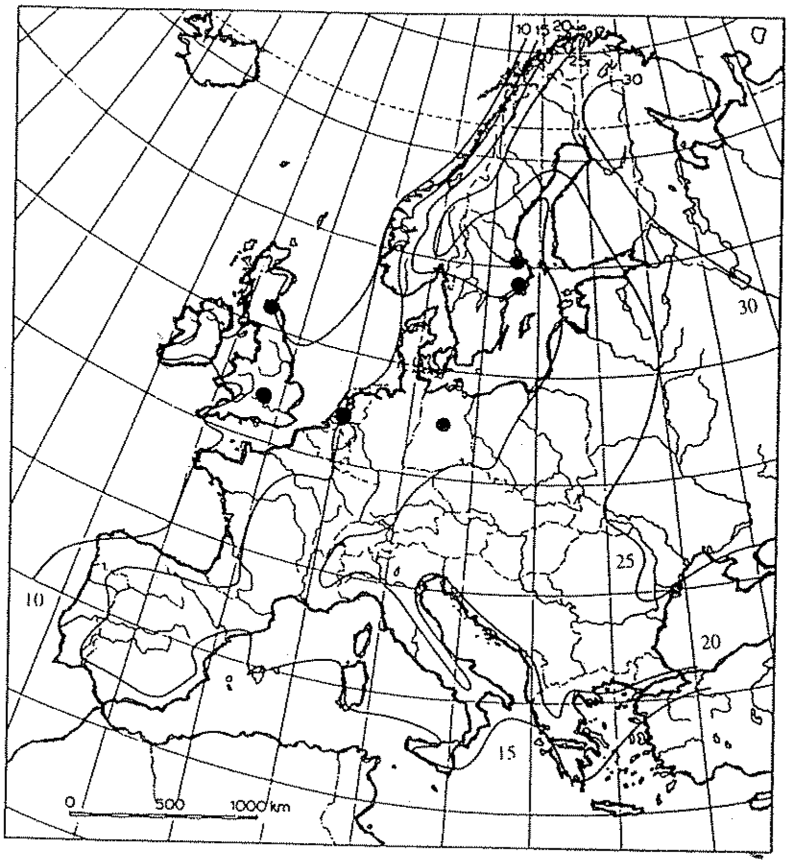

Figure 1. The geographical variation of the annual amplitude of mean monthly air temperature (°C) over Europe. Locations of the six long temperature series discussed in the text are marked by solid circles

identification of aberrant points or gross blunders in data preparation. Then the statistical approach of Alexandersson (1986) was used in order to detect more subtle errors. The basis of the Alexandersson method is to compare one series at a time with a reference series that has been built up from the linear additions of the remaining series. The statistical background to the procedure is described in detail by Alexandersson and Eriksson (1989). A very useful comparison of the Alexandersson method with six other techniques of homogeneity testing has been given by D. R. Easterling and Peterson (personal communication). Easterling and Peterson found Alexandersson's technique to be the most sensitive, of the seven tested, for detecting undocumented discontinuities in times series.

We have six stations with monthly ($m = 1, 12$) temperature measurements (s_{mj}) over $j = 1, N/12$ years. Each of the six stations is taken in turn as a candidate series (Y_t), where $t = 1, N$. A reference series (X_t) is to be constructed for comparison with each candidate series. The first step in the procedure of establishing a reference series is to take all the temperature data of an individual month (e.g. January) and to regress the January data of the five surrounding stations against the January data of the candidate station. An iterative step-up least-squares regression procedure (NAG subroutine G02DAF) is used to calculate the relative weightings (W_{h1}) of neighbouring stations for January ($m = 1$). The iterative step-up regression is then repeated for all 12 months. A reference series is thus formed for each month.

$$X_{mj} = \sum_{h=1}^{5} W_{hm} \times S_{hmj}, \qquad m = 1, 12$$

The 12 regression series are merged to give the full reference series (X_t).

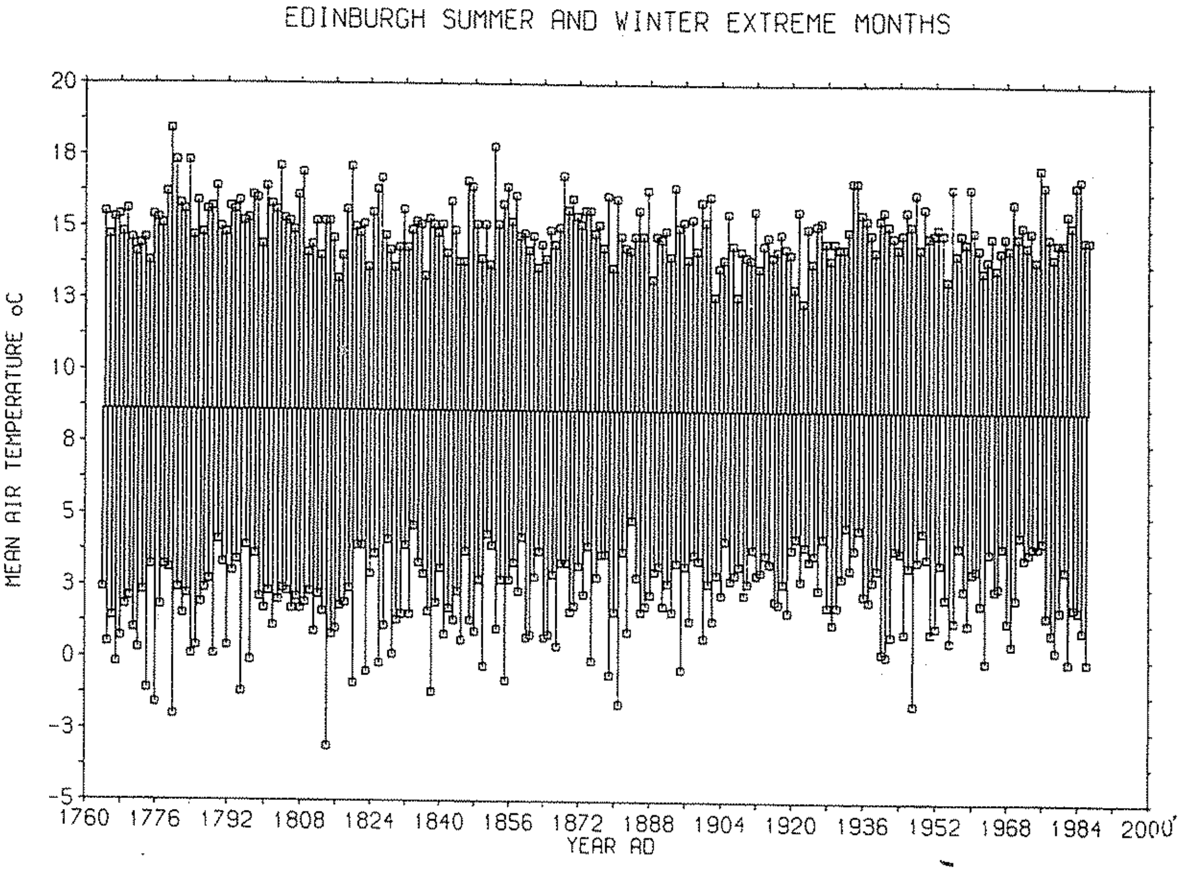

Figure 2. Mean monthly air temperature (°C) at Edinburgh for extreme months of the summer and winter seasons. Note the 20 years between AD 1902 and AD 1922 that had cool summer extremes (14.1 on average) coupled with generally warm winters (1·6 to 4·2). In contrast, observe the block of 17 years from AD 1798 to AD 1815 that had consistently cool extreme winter months (−3·1 to 2·4) combined with relatively warm extreme summer months (14·0 to 17·1)

Differences (Q_t) are now found between the candidate and reference series.

$$Q_t = Y_t - X_t$$

The differences are then standardized to zero mean, unit variance.

$$Z_t = (Q_t - \bar{Q}_t)/\mathrm{SD}(Q_t)$$

where the overbar denotes the arithmetic mean and SD denotes standard deviation.

A time series plot of the standardized differences, Z_t (e.g. Figure 3(a)), can be examined to reveal any outliers, which plot as individual isolated points. Major discontinuities in the temperature data of the candidate series are revealed as clear offsets in the time series plot of the difference series (e.g. February–March AD 1908 in Figure 3(a)). More minor discontinuities are more clearly resolved by calculation of Alexandersson's test statistic T_0.

In order to form the statistic T_0 a breakpoint is moved along the whole length of the standardized difference series, Z_t, and the mean levels calculated before and after the breakpoint. Alexandersson's T_0 is then given by

$$T_0 = \mathrm{maximum}\{T_v\} = \mathrm{maximum}[v \times \bar{Z}_1^2 + (N - v)\bar{Z}_2^2]$$

where $\bar{Z}_1$ is the mean of the standardized difference series from month 1 to v and $\bar{Z}_2$ is the mean from month $v + 1$ to N.

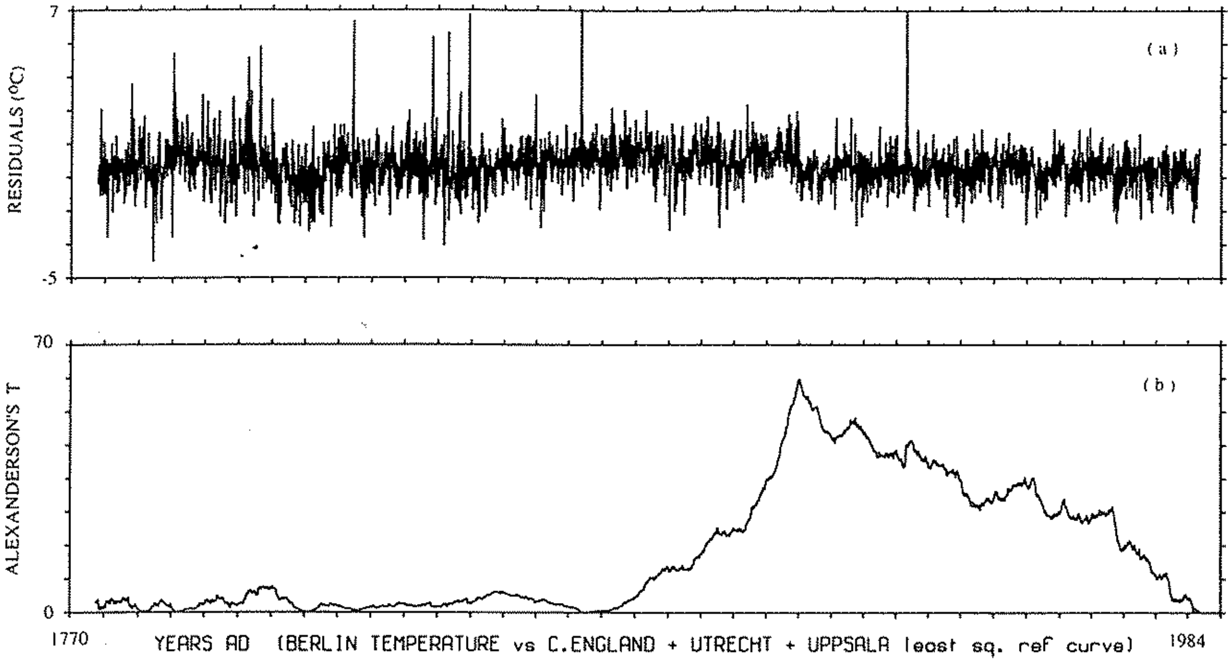

Figure 3. First stage check of the Berlin series for outliers and discontinuities. (a) Standardized difference series. (b) Alexandersson T statistic series. The extreme values in the difference series, i.e. outliers, are to be checked for typographical errors. The discontinuity in the difference series at February–March AD 1908 can be seen to correspond to a maximum in the Alexandersson T values. This part of the time series is to be investigated for a station change in need of correction

The T_v values can be plotted as another time series (e.g. Figure 3(b)). A high T_0 value ($T_0 \geqslant 9{\cdot}25$) corresponds to a time series containing discontinuities. In Figure 3(b) a very high T value of over 61 is found precisely at the February–March AD 1908 jump in the standardized residuals and must correspond to a station change near this time. Indeed consultation of the world weather records, assembled by Clayton (1927), for Berlin and the nearby stations of Breslau and Gutersloh indicates a change at exactly this month of maximum Alexandersson's T value. The main outliers in the difference series of Figure 3(a) relate to transcription errors by the author and so can be easily corrected.

Alexandersson's method was found to be extremely useful and very straightforward to implement and to apply to the long record of European mean monthly temperature. Progressive application of Alexandersson's tests and data correction were used to check and homogenize the six time series before the next stage of data analysis.

Spectral analysis

The second main stage in the data analysis of the six long mean temperature series was to investigate how the variation of temperature might be accounted for by cyclic components at different frequencies. Inspection of a monthly time series of mean temperatures immediately reveals the annual cycle. In order to quantify this behaviour and to find any additional frequency components, spectral or harmonic analysis should be applied. Spectral analysis can be used to analyse data over a wide range of frequencies and to pick out individual periodic components in the presence of noise.

The spectral density function of a time series is most easily estimated from the periodogram (e.g. Chatfield, 1989). Singleton's (1969) mixed radix method was used in the fast Fourier transform (FFT) calculation. The resulting periodogram (e.g. Figure 4) shows how the variance of the times series is partitioned into different harmonics.

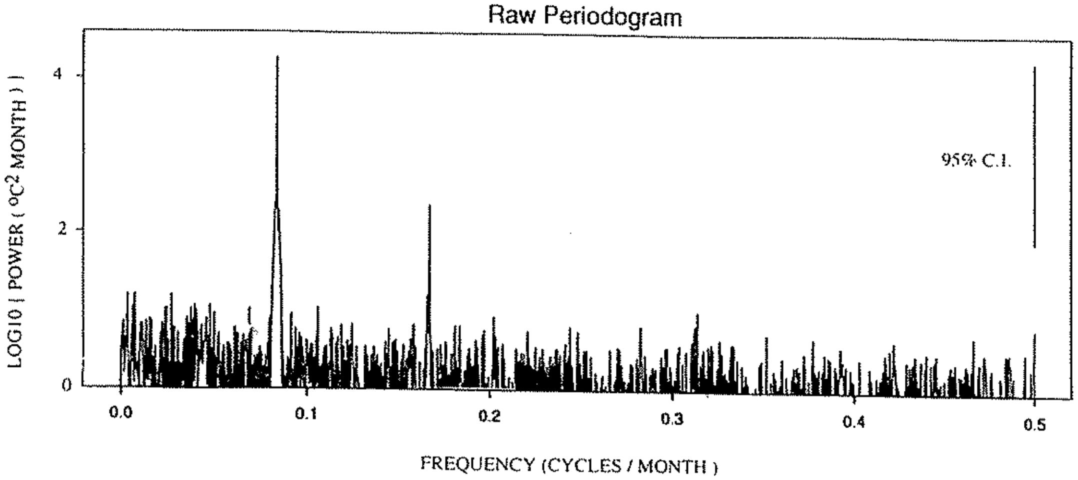

Figure 4. Power spectrum of the detrended, tapered monthly mean Edinburgh air temperature time series. The 1-year and 6-month periodicities stand out as peaks in the spectrum. The variation of the amplitude and phase of the 1-year cycle over the last two centuries is shown in Figure 5

The power of a periodogram at any discrete Fourier frequency, ω_p, is given, in terms of complex numbers, by

$$I(\omega_p) = 1/N \left| \sum_{t=1}^{N} X_t \exp(-2\Pi ipt) \right|^2, \qquad p = 0, 1, 2, \ldots, N/2$$

where $\omega_p = 2\Pi p/N$ is the pth harmonic.

An example of a raw periodogram is shown in Figure 4 for the Edinburgh mean monthly temperature series. The periodogram is dominated, as expected, by the annual cycle at a frequency of 0.08333 (=1/12). A second important cycle is seen in the periodogram at a frequency of 0.1666 (=1/6), i.e. at the six-month cycle. No other cycles stand out. Craddock (1956), working with 5-day means similarly found that a two-harmonic form accounts for almost all the annual variance. Tabony (1984) has discussed the physical origins of this second harmonic in the annual cycle of temperature. No other significant periodicities in the variation of temperature on the time-scale of decades and centuries are seen in these data. The overall decrease in power from low to high frequencies is typical of non-stationary physical processes that display non-periodic variations. Periodograms for the other five time series all show the same features of annual and 6-month cycles combined with variable longer term non-stationary, non-periodic behaviour.

Complex demodulation

Complex demodulation (Bingham *et al.*, 1967; Banks, 1975) is a technique for investigating non-stationary time series. It allows the variation with time, t, of the amplitude and phase of any individual frequency component to be examined. It can be regarded as a local version of harmonic analysis, in that the amplitude and phase of the constituent sinusoids are determined only by the data in the near neighbourhood of t, rather than by the complete time series. The technique is used here to analyse the presumed changes in amplitude of the yearly temperature cycle during the last few hundred years of the six long records of mean monthly air temperature.

Let us suppose that a temperature series, Y_t, can be written as

$$Y_t = R_t \cos(\lambda t + \varphi_t) + \varepsilon_t$$

where R_t is the amplitude at time t of the periodic component with frequency λ and phase φ_t and ε_t is a process without a component at frequency λ. Complex demodulation extracts estimates of R_t and φ_t from the FFT described above (e.g. Figure 5).

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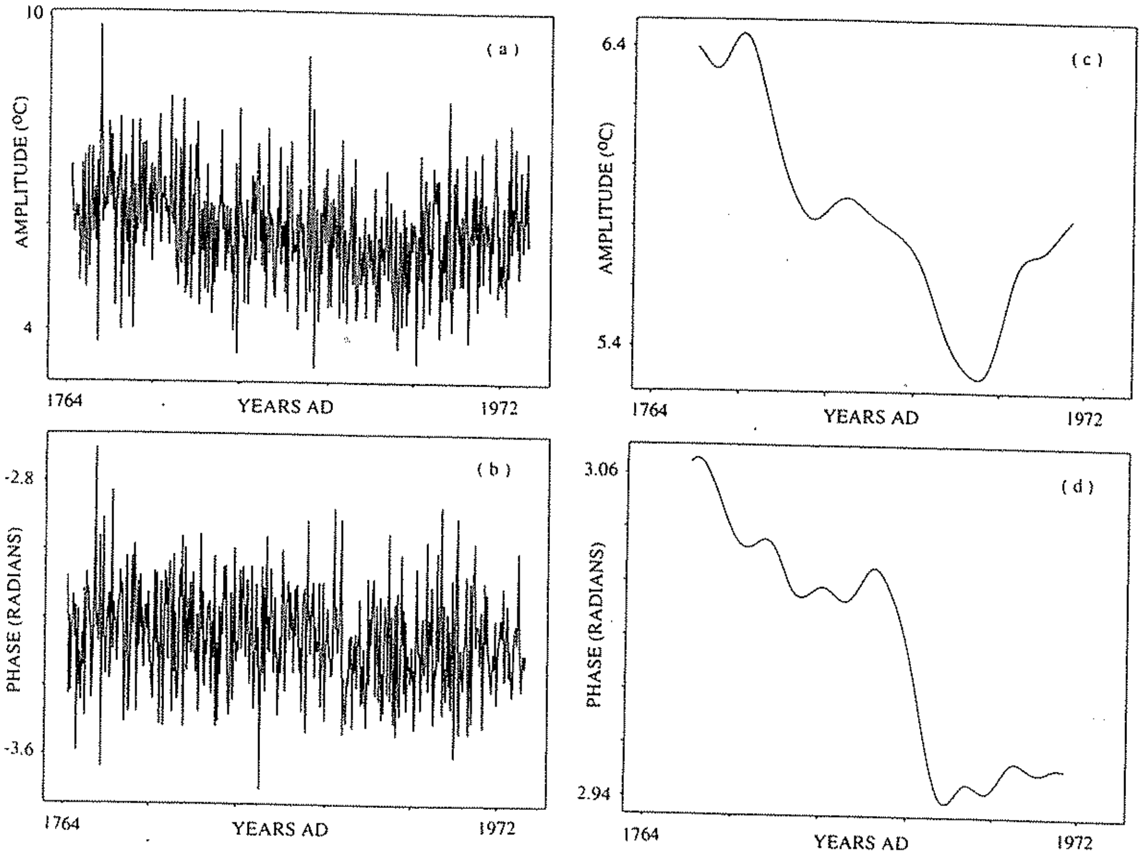

Figure 5. Complex demodulation of the 1-year periodicity of the periodogram of Figure 4 of the Edinburgh mean monthly air temperature time series. (a) Amplitude—no filter; (b) phase—no filter; (c) amplitude—after low-pass filtering; (d) phase—after low-pass filtering. See Text for further details

Complex demodulation was thus the third and final stage in the data analysis of the mean monthly temperature data. A variety of filter lengths were tried to see which yielded results of likely climatological value.

EDINBURGH

We use Edinburgh as an example of the temperature data and their complex demodulation at one station. Extreme winter and summer months from AD 1764 to the present day, in Edinburgh, are plotted, about their mean, as a time series in Figure 2. Visual inspection of Figure 2 reveals times of cooler than average summer temperature (e.g. AD 1902–1922) and warmer than average (e.g. AD 1778–1808). Similarly there are times of generally cooler winters (AD 1799–1820) and conversely of warmer winters (AD 1920–1927). It is apparent that these periods of more extreme conditions are not just caused by a variation in the mean temperature but are related to changes in the individual seasons and to the range of the annual variation.

The raw periodogram of the full ($N = 2664$) Edinburgh mean monthly temperature series of Figure 4 reveals a fairly narrow peak of frequencies centred on the annual cycle and an even narrower peak centred on the six-month cycle. Both peaks stand well above the background level of the continuous spectra on this logarithmic scale periodogram.

Figure 5 shows results of complex demodulation of the full Edinburgh mean monthly temperature series using different low-pass filters. Figure 5(a) and 5(b) show the instantaneous amplitude and instantaneous phase, respectively, of the 1-year oscillation as functions of time without filtering. The effects on the amplitude and phase of low-pass filtering are shown in Figures 5(c) and 5(d). Figures 5(c) and 5 (d) highlight the longer period trends in the yearly range in temperature.

Continentality fluctuations

In maritime areas of Europe (Figure 1) the yearly amplitude of temperature is relatively low. Further inland the amplitude is higher, increasing towards the continental interior (Figure 1). The yearly amplitude of temperature varies in time as well as space (e.g. von Rudloff, 1967). For example, a period of low annual range, when the climate of Edinburgh was more maritime between AD 1902 and AD 1922, is clearly seen in Figure 5(c). The most continental climate experienced in Edinburgh over the last 230 years is seen t in the 1780s and 1800s, some 20 to 40 years after the start of temperature observations in Edinburgh. Phase changes in the annual cycle (e.g. delayed spring and autumn) are seen in Figure 5 to accompany the amplitude changes. The two extremes in both amplitude and phase of the annual cycle clearly can be seen to have occurred in similar time periods (compare Figures 5(c) and 5(d)).

Tabony (1984) has provided a very clear account of the changes in seasonal variation to be expected in mid-latitudes. He discusses and explains the analyses of Craddock (1956) and Smith (1984), of the seasonal variation over the UK, in terms of the first and second harmonics of the seasonal variation, pointing out that increased amplitude variation over continental areas is associated with an advanced phase of the temperature variation compared with the situation over oceans. He shows how a combination of the two main harmonics (the 1-year and 6-month cycle) can lead to a slow rise in temperature in spring with a rapid autumn fall, and that these in turn combine to give a sharp summer peak in temperature over the oceans compared with a sharp winter trough over the continents.

Complex demodulation of the 6-month cycle in the Edinburgh mean monthly temperature record did not reveal any obvious changes over time of either amplitude or phase that matched the changes of the annual cycle.

The secular variation in the harmonics of temperature reported by Smith (1984) for daily observations at Oxford for AD 1811 onwards can be compared with the Edinburgh harmonics calculated from the monthly means. Smith's low annual amplitude of annual variation for the time period AD 1901–30 is in good agreement with the Edinburgh record. This comparison between daily and monthly data gives confidence that useful estimates of annual temperature range are being extracted from the more sparse monthly data by the complex demodulation technique.

CONTINENTALITY FLUCTUATIONS AT ALL SIX STATIONS

Precisely the same complex demodulation and low-pass filtering as used on the Edinburgh data have been applied to the other five long records of mean monthly temperature. The complex demodulate amplitude results are shown in Figure 6. Very satisfyingly the main trends found for Edinburgh are to be seen at all the other stations. Decadal long continentality fluctuations thus occurred at stations with pronounced continental climates (e.g. Uppsala, Figure 1) as well as at the more maritime localities of Edinburgh and Central England (Figure 1). In order to be able to compare the amplitude variations of the six stations more easily the complex demodulates were standardized to zero mean and unit variance over the period of their overlap (August AD 1790 to May AD 1970). Note that the overlap period of the complex demodulates is slightly shorter than the overlap period of the full time series data on account of the filter length.

In Figure 7 one very noticeable distinct time period is the maritime period of the 1920s, which is seen as a trough in all the graphs. The 1770s and 1800s with their more continental climates also show as noticeable time periods, at all six stations, as peaks in the continentality index.

One obvious difference in the patterns of changing continentality is the amplitude variation at Uppsala prior to about AD 1825, which seems about 0.6°C lower than might be gauged from the fluctuations in later decades. A second difference relates to the high amplitudes of annual variation derived from the Berlin temperature series in the 1850s and 1860s. These single-station differences will need additional studies,

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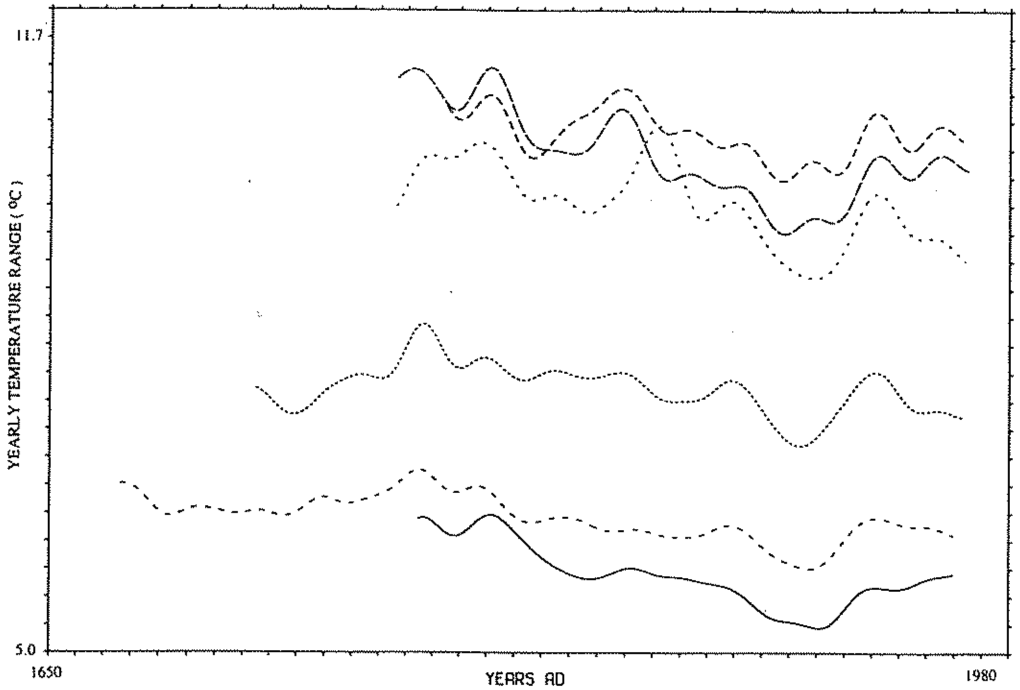

Figure 6. Complex demodulation of the amplitude of the 1-year periodicity of the mean air temperature at all six stations. The amplitude of the yearly variations of the records increases from Edinburgh (solid line) through central England (widely spaced dashed line), De Bilt (short dashed line), Berlin (dashed line) and Stockholm (long dashed line) to Uppsala, as would be expected from their location (Figure 1) and relative proximity to the North Sea and Atlantic Ocean. Note how unusually low temperature ranges are found for all stations in the early 1900s. In contrast note that unusually high annual temperature ranges are found, at all six stations, in the 1770s and 1800s. The long Manley record of central England also exhibits high annual temperature ranges in the 1670s. Berlin had unusually high annual temperature ranges in the 1860s in contrast with the other five stations

particularly of the records from neighbouring stations, in order to decide if they have any climatological significance or conversely if they are connected with purely local observational or instrumental difficulties. The phase changes in the annual variations do not repeat between the six stations as well as the amplitude changes.

Long-term (11 years) averages of the seasonal change of air temperature and of precipitation have been estimated by Pfister (1992), for the pre-instrumental period, for Switzerland. His important historical studies have allowed continuous series to be formed from AD 1535 to the present. Differences between the summer and winter mean temperatures of his remarkable series have been calculated and plotted in Figure 8, as a rough measure of continentality during the last 460 years. The most striking feature of Figure 8 is how the maritime period of the 1920s is revealed as by far the most extreme change in continentality since AD 1535. From Pfister's data the 1770s once again are found to have been very continental in character, although this is not the case for the 1800s. Considering all the difficulties associated with reconstructing Renaissance and early Modern temperature records, Manley's and Pfister's seventeenth century data agree very well. The main difference between the two series, in terms of continentality, is in the 1690s and 1700s. During these two decades Manley's British compilation is indicative of rather typical continentality whereas Pfister's Swiss data point to very extreme continentality. A further difference concerns the early part of the Utrecht series (Figure 7), which plots out consistently more marine in character, on the continentality index of Figure 7, than either Pfister's or Manley's data for the period before AD 1770. These lower yearly temperature ranges in The Netherlands may partly reflect the change of observation site from Delft/Rijnsburg to Zwanenburg in January AD 1735. Application of Alexandersson's test to the complex demodulates, rather than to the temperature data, might be anticipated to be able to help detect these types of potential inhomogeneities.

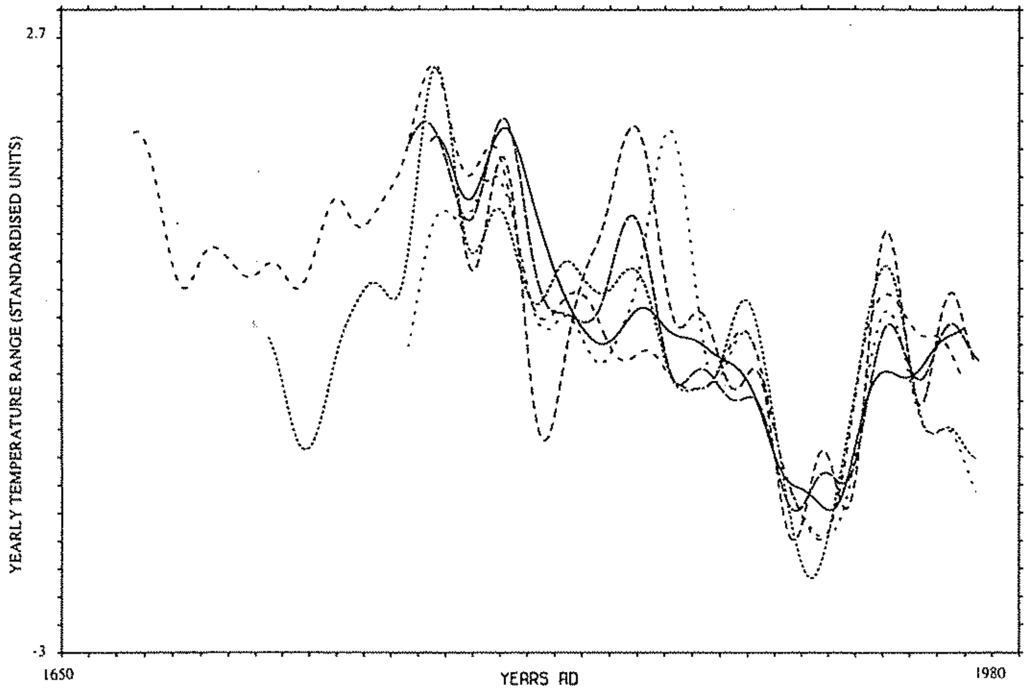

Figure 7. Standarized complex demodulation of the yearly amplitude for all six stations. Legend as Figure 6. The amplitudes of the overlapping years AD 1790–1970, following low-pass filtering) have been standardized to zero mean and unit variance. The early decades of the long central England and De Bilt mean air temperature series show higher than average continentality. Consistent pronounced continentality is seen at all six stations in the 1770s and again in the 1810s. Marked geographical variations in continentality occurred in the mid- to late eighteenth century. Average continentality conditions prevailed once again in the 1890s. There then followed a period of widespread oceanicity in the 1920s. The 1940s once again exhibited more pronounced continentality. Recent decades in Europe have provided rather average continentality conditions

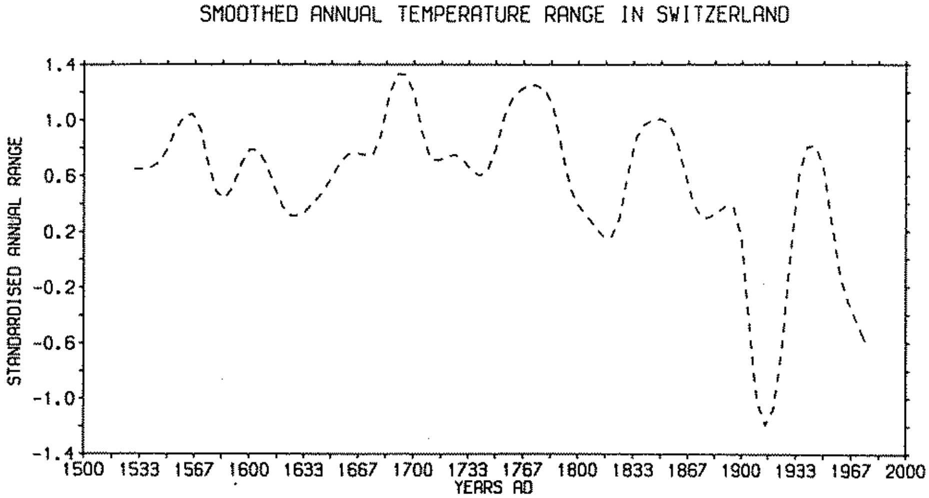

Figure 8. Change in continentality since AD 1535 in Switzerland. The dashed curve shows the smoothed long-term range of annual temperature as based on the differences of Pfister's (1992) compilation of winter and summer temperatures using 11-year averages

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CONCLUSIONS

(i) The changes with time of the continentality of climate are found, using a complex demodulation technique, to be coherent over large areas of Europe.

(ii) The 1770s and 1800s displayed maxima in continentality in regions ranging from the maritime climes of Britain across to the more continental climate of the interior of Scandinavia.

(iii) The 1910s and 1920s displayed the lowest level of continentality ever witnessed during the last 460 years in Europe. A similar degree of change from continentality towards oceanicity was recorded in Britain, the Low Countries, central Europe, Scandinavia, and the Alps.

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