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A time-series analysis of the changing seasonality of precipitation in the British Isles and neighbouring areas

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Abstract

Complex demodulation of monthly precipitation data is used to determine temporal changes in the decadal averages of the annual precipitation cycle. Good spatial coherence is found between sites from as far apart as Scotland, western Ireland and southern Sweden. The annual precipitation cycle is found to have been unusually late in the 1870s and early 1900s and to have been noticeably early in the 1860s and 1890s. Fluctuations of up to 13 weeks are found in the timing of the annual precipitation cycle, as recorded at Kew, during the last 300 years. Complex demodulation provides a technique to quantify annual climate changes and hence to provide a quantitative context in which detection of anthropogenic-induced changes to the annual climate signal can be assessed. Ten percent changes in the decadal averages of the amplitude of the annual precipitation cycle and in precipitation amounts are found. Although precipitation in the British Isles is often cited as rising, no persistent increases are observed in this study. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Precipitation; Annual; Cycle; Amplitude; Phase; Britain

1. Introduction

The British Isles lie in mid-latitudes on the western seaboard of Europe and consequently enjoy a moist and temperate climate of great variety. Manley (1970) points out that no other climatic type is more provocative of comment and that by some it is described as the most agreeable in the world. Temperate oceanic climatic zones are restricted to the western margins of the continents, on account of the prevalence of westerly air flow. In North and South America the north–south alignment of major mountain chains restricts the oceanic climatic zone to a rather narrow coastal strip. However, in Europe, maritime air masses and depressions can penetrate more easily inland and a more extensive oceanic climatic zone is found.

The weather and climate of the temperate oceanic zones of the world are notoriously variable, both temporally and spatially. Precipitation exhibits even more complexity and variability than other climatic parameters such as air temperature and pressure. Precipitation is surprisingly difficult to measure accurately as modifications to instrumentation and small site changes can have profound effects. Furthermore topography has a marked effect on precipitation. Also precipitation does not frequently fall in showers or thunderstorms of limited geographical extent. Not surprisingly precipitation data series from only a few kilometres apart can sometimes show little similarity or coherence.

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The British Isles have particularly extensive and reliable precipitation records. These observation series were largely begun by dedicated amateur observers. Their results have been collated, preserved and synthesised by the unremitting efforts of later enthusiasts such as Symons and Glasspoole. The spatial patterns of precipitation in Britain have been particularly lucidly summarised by Salter and de Carle (1921) and updated, for England and Wales, by Wigley et al. (1984), Wigley and Jones (1987), Jones and Conway (1997) and Jones et al. (1997a).

The aim of the present work is to apply modern time-series analysis, particularly complex demodulation, to precipitation series in order to investigate their temporal fluctuations. Complex demodulation allows fluctuations in the amplitude and phase of periodic cycles, such as the annual cycle, to be determined. The elucidation and documentation of the natural variability of climatic parameters, and their fluctuation on decadal and centennial time scales, are now vital for assessing the impact of anthropogenic gases on the climate system and the early detection of greenhouse-gas-induced climatic change.

2. Theory

The technique of spectral analysis (e.g. Jenkin and Watts, 1968) gives information on the cyclicities present in a time-series. However it assumes stationarity, i.e. that the frequencies in the data are sinusoidal in nature and constant throughout the whole data series. In contrast, complex demodulation (Bloomfield, 1976) allows for slow fluctuations in the periodic components. Through the application of a low-pass filter, it permits any fluctuations in amplitude and phase of a sinusoid to be recovered from a time series. Complex demodulation is thus ideal for analysis where the approximate frequencies present in the data are already known and one is interested in the temporal behaviour of the periodicities. Following Bloomfield (1976) we assume that the data $\{x_t\}$ contains a periodic component

$$R_t \cos(\lambda t + \varphi_t),$$

where R_t is a slowly changing amplitude, φ_t is a slowly changing phase and λ the frequency of interest, i.e. R_t is the amplitude, at time t, of the periodic component with frequency λ, and φ_t is the phase, at time t, of this component. In order to perform complex demodulation the time-series $\{x_t\}$ is first frequency-shifted by multiplication by $e^{-i\lambda t}$. Then low-pass filtering of the shifted time-series can be used to remove the higher frequency components plus the noise and so allow the smooth, lower frequency information of interest to be determined. Such a low-pass filter effectively acts as a band-pass filter when the time series is reconstructed. The resulting complex time series is finally re-expressed in terms of the time variations of the amplitude and phase of the frequency, λ. A least-squares approximation method (Bloomfield, 1976) is used to design suitable filters and permit efficient complex demodulation.

3. Previous work

3.1. Time-series analysis

Early frequency analysis involved fitting climate data with a sum of sine and cosine terms, often using the well known Fourier series. A good example of this type of analysis is the work of Brunt (1925). Many authors have continued to search for periodicities in climatic records. However the extraction of periodicities from noisy data is not straightforward and little if any consistency is to be found between the many reported climatic cyclicities. Tabony (1979) gives a clear example of the problems associated with the application of the maximum entropy approach to spectral analysis of climate data. He shows how repeated application of the maximum entropy technique using different order autoregressive models results in quite different apparent periodicities and how it can generate quite spurious peaks. As Schuurmans (1984) points out "despite the considerable effort by various climatologists … real periodicities… (except for the annual variation) have been difficult to detect." He also notes that "von Rudloff (1967) even concludes that … periodic changes most often are merely to be considered as unimportant computational results".

The complex demodulation technique, which does not search for periodicities but analyses the temporal behaviour of known cyclicities, has seen little application in climate studies. Thompson (1995) used the method with long (>200 years) series of monthly mean air-temperature data from Europe and found consistent fluctuations in the amplitude of the seasonal signal from sites as far apart as Scotland, the Gulf of Bothnia and the North European Plain. Subsequent work (Buchan, 1995; Treacy, 1996) has shown how this pattern of the seasonal variation in air temperature, particularly the low seasonality of the 1920s, extends eastwards to Leningrad, south-eastwards to Budapest and southwards to Milan, an area of about 10^7 km^2. Thompson (1995) also found that the phase of the annual temperature cycle at Edinburgh, as revealed by complex demodulation, has changed by about six to seven days during the last 200 years, the main shift taking place around 1900.

Thomson (1995) proposed that the phase of the annual temperature cycle, over the last few hundred years, has mainly been controlled by the precession of the perihelion rather than precession of the equinoxes. He suggested that the phase of climate change should therefore change at a rate corresponding to the difference between the lengths of the anomalistic and tropical years, rather than remain in concert with the Gregorian calendar. In addition Thomson (1995) found that, since about 1950, the phase of the annual air-temperature cycle has become anomalous by about a further seven days. He argued that this phase change in the seasonal cycle in temperature is caused by a CO_2-enhanced greenhouse effect. Keeling et al. (1996) report phase advances of about seven days of the declining phase of the seasonal cycle of atmospheric CO_2 at Mauna Loa (Hawaii) and Barrow (Alaska) between the 1960s and the 1990s. They attribute these changes to a lengthening of the growing season. They also find an increase in the amplitude of the annual CO_2 cycle, which appears to reflect global-warming episodes and increased activity of northern vegetation. Mann and Park (1996) have analysed the average air-temperature record of the northern hemisphere and found the complex demodulation technique to identify phase changes to an accuracy of one day. They noted a decreasing amplitude in the seasonal air-temperature cycle commencing about 1950. Furthermore they were able to illustrate the spatial patterns of the phase and amplitude of the annual temperature cycle for the whole of the northern hemisphere using a multivariate generalisation (Mann and Park, 1996) of the complex demodulation method.

3.2. Characteristics of British rainfall

It has long been recognised that the mountainous regions of the British Isles are much wetter than the lowlands and that western areas are wetter than eastern areas. Much of western Scotland and Ireland experience over 250 rainy days per year compared with fewer than 170 rainy days in the south and east of Britain. In most countries of the world rain falls in a particular season, but in many parts of the British Isles the distribution of rainfall throughout the year is rather even. However the wetter parts of the British Isles tend, on the whole, to have more rain in the winter than the summer. The relative seasonal frequency of precipitation in Britain was well understood by the 1920s and Salter and de Carle (1921) presents many maps that neatly characterise the complexities of the pattern of rainfall in Britain. These illustrate the many differences of the precipitation of the westerly uplands from that of the easterly plains. He notes that “on account of the great and capricious fluctuations to which rainfall is liable at all seasons, the normal seasonal march may in individual years be completely masked”, and so emphasises the need for temporal averaging in order to detect any coherent temporal variations in precipitation.

An early study of the temporal variations in precipitation was also that of Salter and de Carle (1921). He analysed the fluctuations in annual rainfall from 1860 to 1919 across Britain and recognised a period of heavier than usual precipitation in the 1870s and drier than usual conditions in the years around 1890. Tabony (1981) greatly improved our knowledge of European precipitation patterns by assembling 182 homogenised European precipitation series. He identified increases in precipitation, during the previous 110 years, in a belt stretching from southwest France to southwest Scandinavia and mapped the proportion of rain falling in the summer months across much of the western Europe. Wigley et al. (1984) and Wigley and Jones (1987) examined the records from 55 sites and divided England and Wales into five precipitation regions. They concluded that precipitation values have not been changing appreciably, on time scales of 30 years or more, in any of the five regions although there has been considerable variety on time scales of the order of a decade or less. The one change they noted that appeared to be statistically significant in the

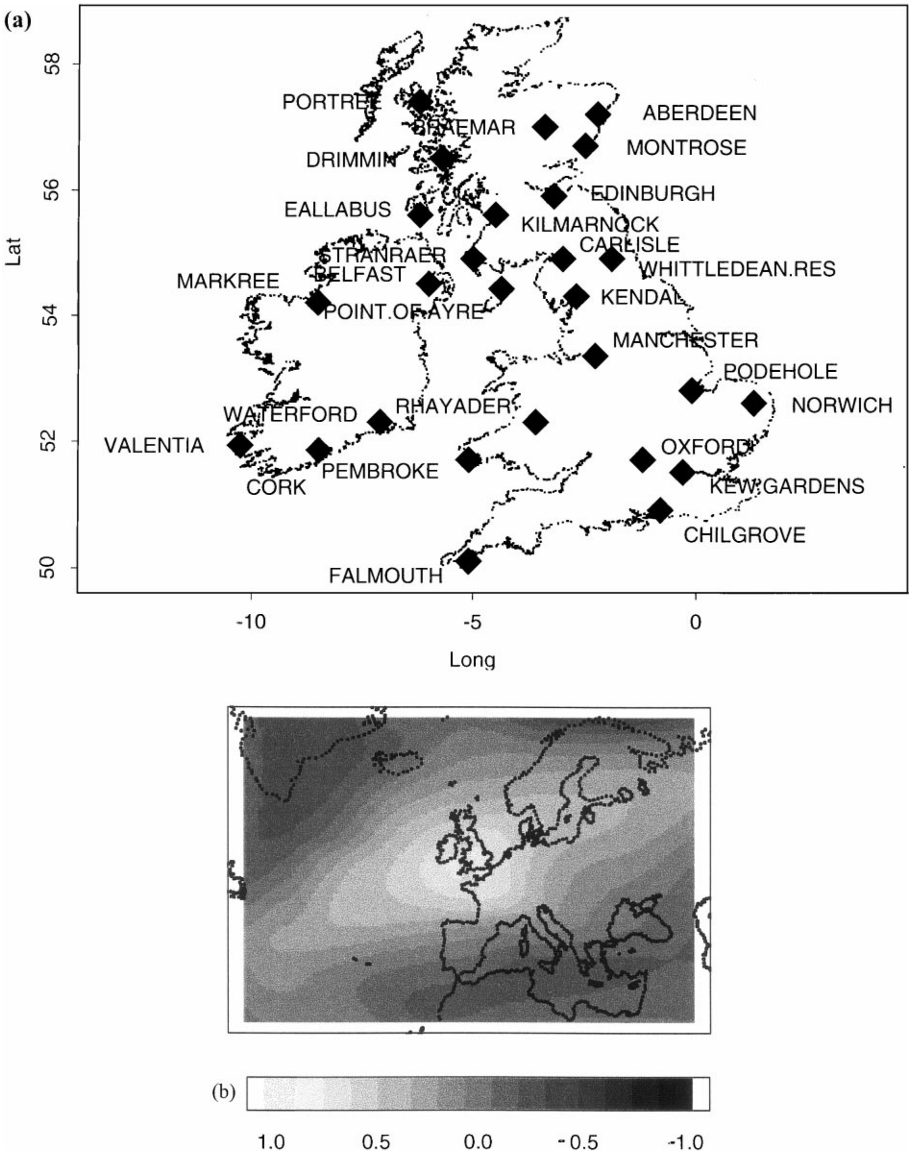

Fig. 1. (a) Location of 27 long British and Irish precipitation series with monthly data from at least 1862. (b) Correlations with the Oxford precipitation record during the month of February. Correlation coefficients over land have been calculated from the series shown in (a) and listed in Table 1. Correlation coefficients over the north Atlantic have been calculated from MSU data and are used to set the British precipitation records into a wider context. A south-west to north-east trend (following the main depression tracks) is seen in (b). Positive correlation coefficients are found throughout the central region of this south-west to north-east elongated ovoid.

previous 10 years (1976–1985) was an increase in the frequency of dry summers and wet springs. However Gregory et al. (1991) found no further examples of the tendency to wetter springs and drier summers after 1985. More recently Mayes (1996) has examined the changes in precipitation during the period 1941–1990 in a large number (~199) of British records. He reports an enhanced seasonal cycle with increases of precipitation in autumn, winter and early spring in western areas and increases in the late spring and early summer in eastern areas in the 30-year averages.

On a European scale, the one coherent aspect of

Table 1
Characteristic of precipitation and its annual cycle

Station	Number of years	First year	Median (mm/day)	Range (mm/day)	Phase (day[a])
Aberdeen	118	1871	1.9	1.2	289
Belfast	158	1819	2.7	1.7	304
Braemar	117	1857	2.2	1.7	320
Carlisle	143	1845	2.0	1.4	266
Chilgrove	154	1834	2.2	1.9	313
Cork	153	1836	2.6	2.3	346
Drimnin	127	1850	3.9	3.3	324
Eallabus	189	1800	3.1	2.6	322
Edinburgh	203	1785	1.6	1.2	252
Falmouth	153	1835	2.7	2.6	339
Hoofddorp	239	1735	1.8	1.8	265
Kendal	168	1820	3.2	2.5	314
Kew-Gardens	291	1697	1.5	1.0	262
Kilmarnock	126	1851	2.8	2.0	305
Lund	229	1748	1.5	1.2	260
Manchester	203	1786	2.2	1.5	272
Markree	143	1833	2.9	1.8	307
Montrose	145	1844	1.7	1.2	279
Norwich	150	1836	1.6	1.1	282
Oxford	222	1767	1.6	1.1	267
Paris	219	1770	1.5	0.9	235
Pembroke	139	1849	2.0	1.8	322
Point-of-Ayre	154	1823	1.9	1.5	310
Pode Hole	262	1726	1.4	1.0	252
Portree	117	1860	2.3	1.6	297
Rhayader	130	1858	4.0	3.5	340
Stranraer	159	1817	2.6	1.9	314
Valentia	129	1861	3.7	2.9	337
Waterford	129	1843	2.5	1.7	326
Whittledean	138	1850	1.6	1.1	254

[a] Day of maximum annual precipitation cycle (1 January = day 1).

precipitation patterns picked out by Flohn (1984), in his review of European precipitation, was a 10–15% increase in winter precipitation when averaged over the period 1885–1940. Groisman (1991) and Bradley et al. (1992) both identified Scandinavia and northern Europe as a region of enhanced precipitation. Their findings have recently been confirmed by Førland et al. (1996) who, following a detailed homogenisation study, concluded that European precipitation around the periphery of the North Atlantic had increased by 10% between the periods 1931–1960 and 1961–1990. Førland et al. (1996) also suggest that continental parts of Europe have experienced a more stable climate during the period 1931–1990, with Britain lying across the boundary between the two precipitation regimes.

4. Data

Monthly precipitation data were extracted from the Global Historical Climate Network (GHCN) database (Vose et al., 1992). The British part of the GHCN database is largely built on the compilations of Tabony (1981) and Jones, Hulme and Wigley (see Jones et al., 1997a). Three selection criteria were used to choose British and Irish records for analysis: (i) the data series spanned at least 117 years; (ii) the data series was continuous; (iii) comparison of data between nearby sites yielded no immediately obvious differences in the data series. Following the application of these three selection criteria, 27 records were obtained for time-series analyses. The locations of these 27 records are shown in Fig. 1a. Three

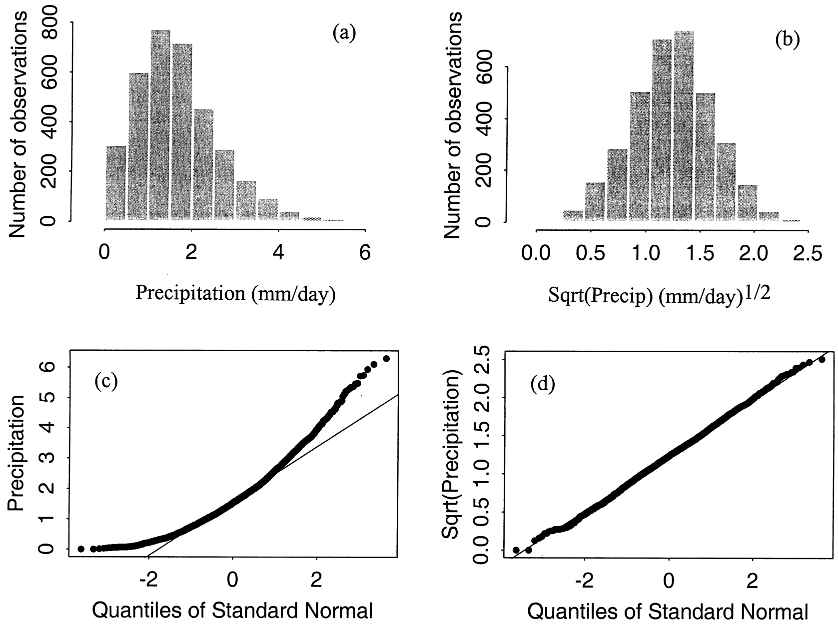

Fig. 2. Histograms and *Q–Q* normal probability plots of precipitation (a) and (c) and the square root of precipitation (b) and (d) as measured at Kew. The straight lines in the normal probability plots are drawn through the upper and lower quartiles. Notice how for the square root of precipitation the normal probability plot (d) exhibits little curvature and only shows modest departures from the straight line of a normal distribution.

precipitation records from further to the east and south, namely Lund, Sweden; Paris, France; and Hoofddorp, The Netherlands, were also analysed for comparison (Table 1). The average length of all 30 precipitation records is 166 years. Step (iii) in the selection procedure resulted in precipitation records from Leeds, Althorp Park, Shifnal and Fort William being removed from the collection of sites. Nevertheless a good geographic coverage of sites across the British Isles remains for the time-series work (Fig. 1a).

The longest continuous precipitation record from anywhere in the world is from Kew. This record began in January 1697. Like all long historical series it has been built up from a number of stations and the later data are likely to be the more reliable. A histogram of the 3492 data points from this 291-year long record (Fig. 2a) revealed a heavily skewed distribution with more months being drier than the mean (1.7 mm/day), and a few months much wetter than the mean. A square-root transformation was found to generate a symmetrical bell-shaped distribution (Fig. 2c). Fig. 2b and d illustrates a graphical method of assessing non-normality. They display the sample versus the expected value if the data came from a normal population. This type of plot approximates to a straight line if the data are from a normal distribution but exhibits curvature if the population is not normal. The square root of the Kew precipitation data is similar to that of a normal distribution (Fig. 2d). Other British precipitation records were found to exhibit similar distributions. All records were analysed using the square-root transformation, but converted back into the original measurement units for interpretation.

4.1. Variation between sites

Table 1 tabulates the average (median) precipitation at the 30 sites analysed. It varies from 4 mm/day at Rhayader in Wales, 3.9 mm/day at Drimnin in western Scotland and 3.7 mm/day on the southwest coast of Ireland, at Valentia, to 1.4 mm/day on the eastern side of England at Pode Hole. The seasonal variation also shows wide between-site variation. The largest range in the annual variation of precipitation

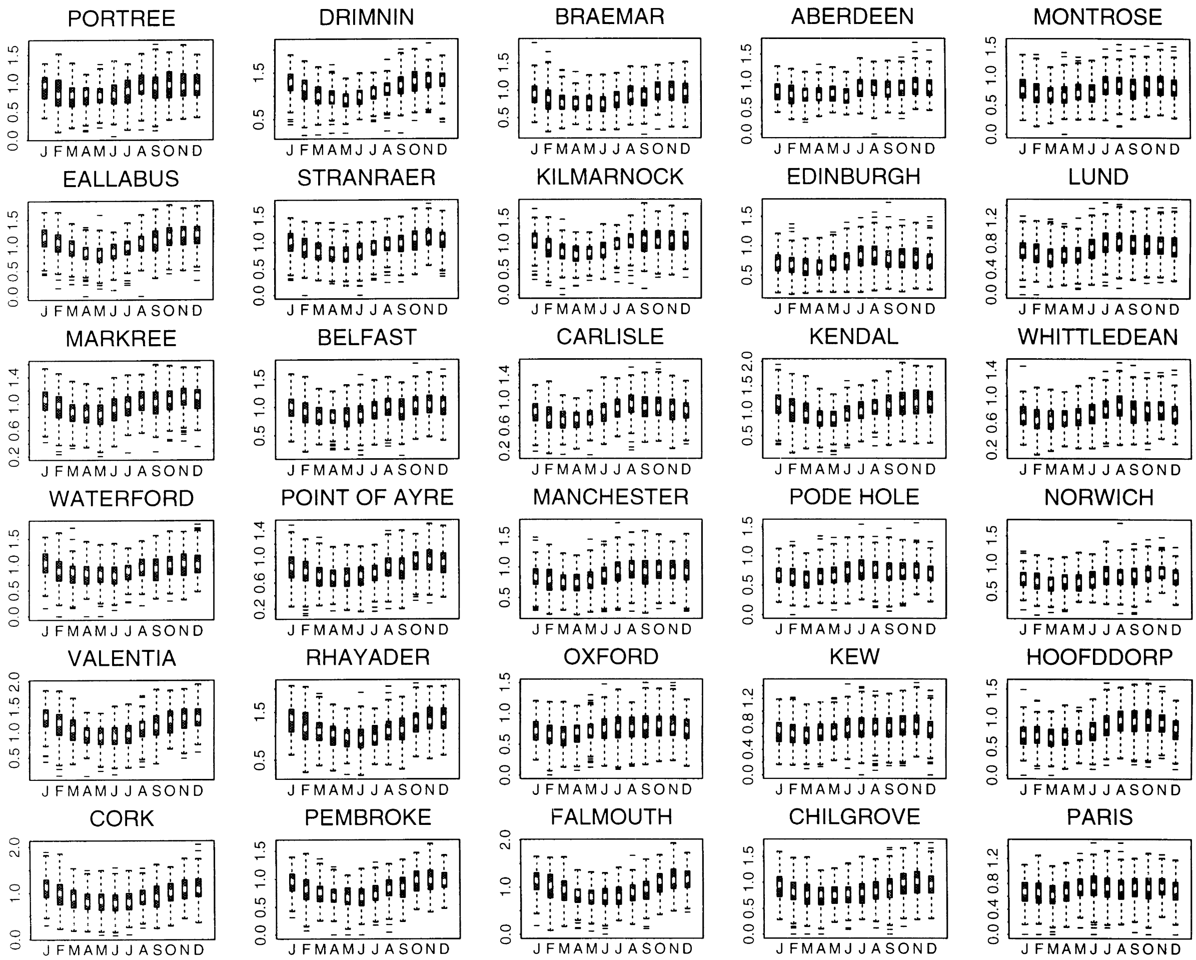

Fig. 3. Boxplots of the square root of the precipitation at 30 localities, arranged approximately according to their geographical position. The boxplots show the median, quartiles and outliers in the distributions of precipitation. The tendency for winter precipitation in more westerly/oceanic regions, e.g. Cork, but for summer precipitation in easterly localities, e.g. Edinburgh can be seen. Intermediate sites e.g. Carlisle show a double maximum or little seasonal variation. All precipitation values expressed as $(\mathrm{mm/day})^{1/2}$.

(i.e. twice the amplitude of the annual cycle) is 3.1 mm/day at Drimnin and Rhayader. The site with the lowest annual precipitation range out of the 30 studied is Paris where the difference between the wettest and driest months averages just over 0.5 mm/day. The timing (phase) of the annual precipitation cycle also varies greatly between the sites studied. The sites with the most extreme phases are Cork, with its maximum rainfall in December and Paris with its maximum in August. Fig. 3 illustrates these variations in a graphical form.

4.2. Spatial coherence of the data

The calculation of between-site correlation coefficients provides a straightforward method of quantifying the spatial variability of monthly climate series. The spatial coherence of British precipitation is illustrated in Fig. 1b. Here the correlation coefficients with respect to the precipitation at Oxford are contoured for February. The highest correlations form a band running from south east of Newfoundland, across southern Britain to southern Finland. This band is flanked by zones of negative correlations

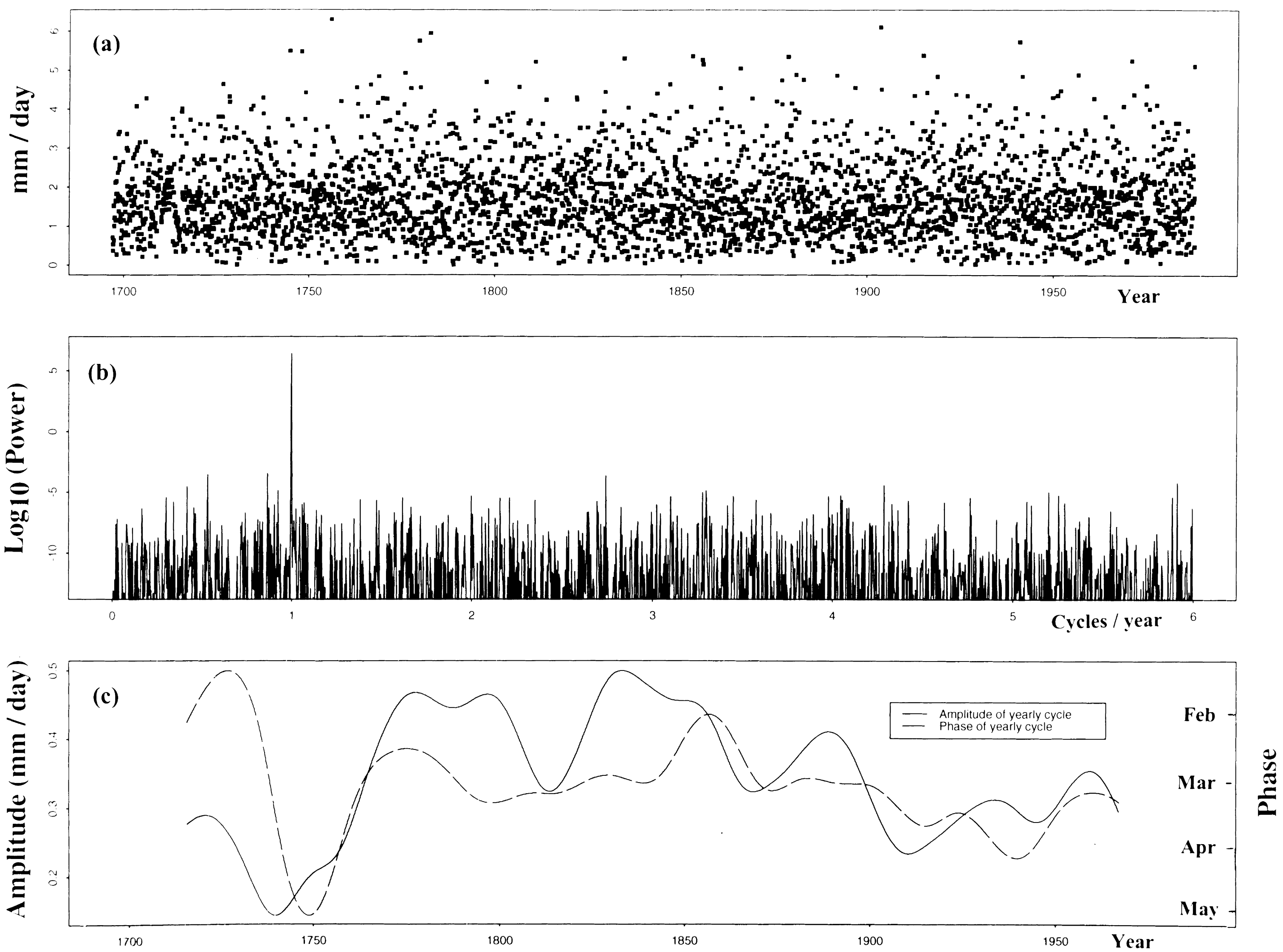

Fig. 4. The Kew precipitation time series. (a) Monthly averages. (b) Raw periodogram. Note the only strong peak is for the annual cycle. (c) Amplitude (solid line) and phase (dashed line) of the minimum in the annual cycle.

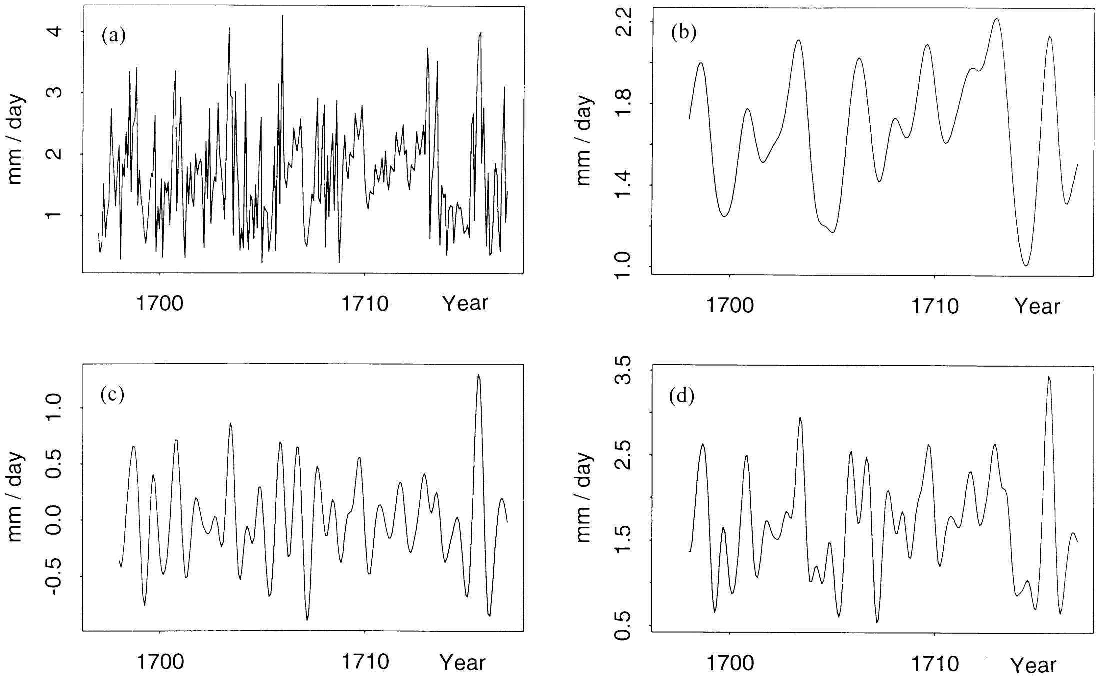

Fig. 5. Complex demodulation of the first 20 years of the Kew precipitation record. (a) Raw data. (b) Smooth component produced by low-pass filtering. (c) Annual cycle isolated by complex demodulation (d) Reconstruction of the Kew series using (b) plus (c). All graphs plot precipitation (mm/day) vs. year.

which run from south of Greenland to the Norwegian Sea and from south of the Azores into the Mediterranean. Correlations across Britain fall from +0.7, at the closest sites to Oxford, to low *r*-values of below +0.2 in north-western areas. In comparison, correlations remain somewhat higher ($r > +0.4$) with sites at greater distances from Oxford but lying further to the east, for example in the Netherlands. An elongated ovoid of coherence trending E–W, is thus observed. It presumably reflects the eastwards passage of depressions and frontal systems across Britain. The spatial coherence patterns for other months are not dissimilar to that for February. However, higher correlation coefficients are found during the winter months. Even so the overall spatial coherence of monthly precipitation is found to be much lower than for air temperature or pressure, where correlation coefficients are more typically between +0.8 and +0.9 for sites 100–500 km apart. While the precipitation–correlation map mainly reflects the tracks of rain-bearing depressions, temperature–correlation maps mainly reflect the wind paths of warm- and cold-air advection. Thus temperature–correlation maps have less elongated ovoids of coherence and exhibit negative teleconnections over distances of a few thousand km owing to air flow around large pressure system.

5. Results

5.1. Periodograms and complex demodulates

Results of the time-series analyses are illustrated using the Kew precipitation series in Fig. 4. The upper panel shows the precipitation data plotted as a time series. The middle panel shows the Fourier spectrum (raw periodogram) which has just one predominant cycle, the annual cycle. The lowermost panel shows the fluctuation in amplitude and phase of the annual precipitation cycle, as reconstructed by complex demodulation, using a low-pass filter. Bloomfield's (1976) least squares approximation method was used to construct a filter with a pass frequency of 1/20-years for the analyses of Fig. 4.

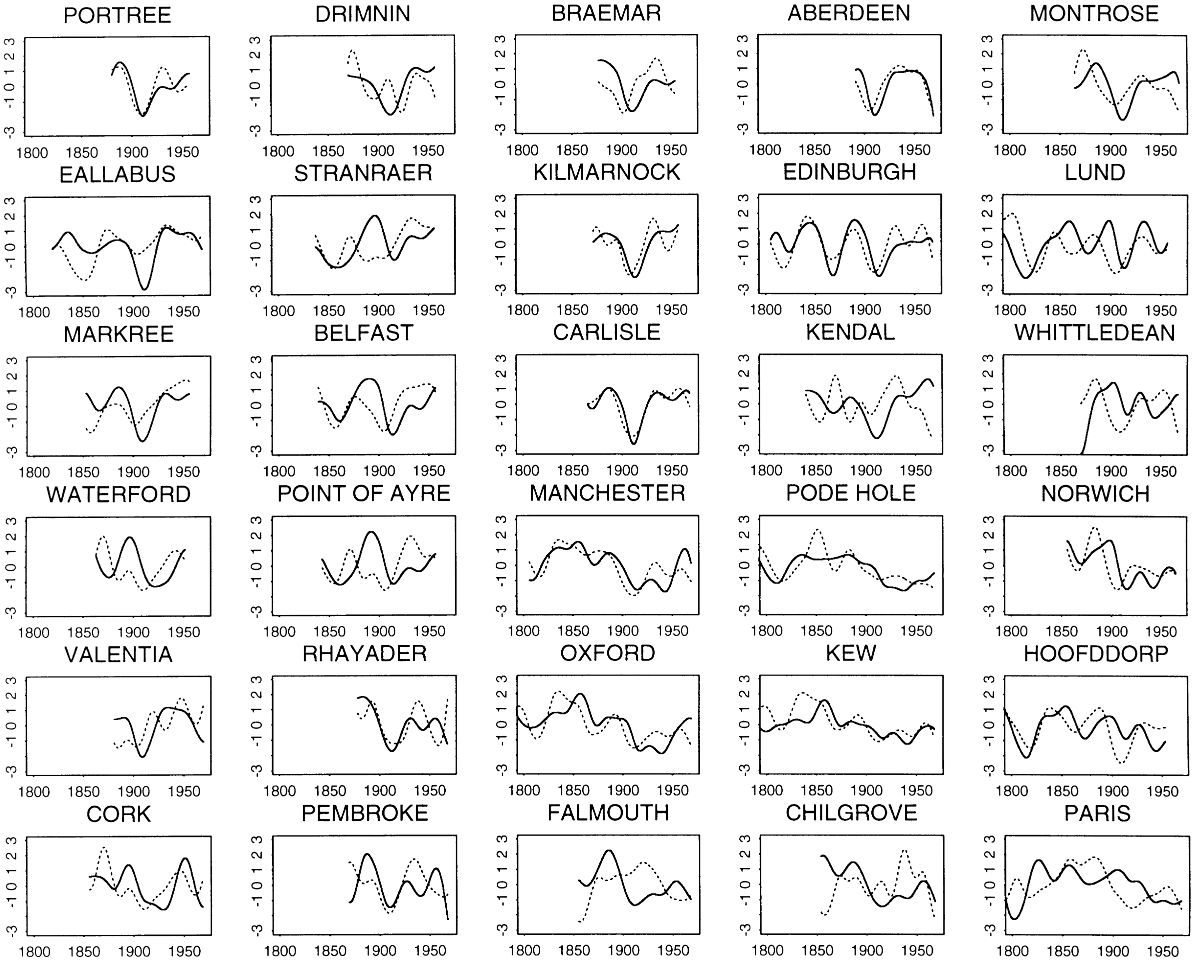

Fig. 6. Changes with time in the amplitude (solid lines) and phase (dashed lines) of the annual precipitation cycle for 30 localities. The stations are arranged as in Fig. 3, approximately according to their geographical position. Amplitudes and phases scaled to zero mean and unit variance.

The amplitude of the annual cycle is found to have varied from the highest values of around 0.5 mm/day per year in the 1830s to the lowest values of some 0.15 mm/year in the 1740s. Over the last 150 years the amplitude of the annual cycle, as recorded at Kew, has tended to decrease slightly. Despite the rather weak annual precipitation cycle at Kew (see Fig. 3) complex demodulation has been able to extract its characteristics without difficulty.

Fig. 5 illustrates in more detail the success of complex demodulation at extracting the annual precipitation cycle. Here just the first 20 years of the Kew data are shown. Fig. 5c plots the annual component extracted using as little smoothing as possible (i.e. using a low-pass filter with a pass frequency of one cycle per year). The annual cycle (Fig. 5c) when added to the smooth trend (Fig. 5b) produces a good fit (Fig. 5d) to the original data (Fig. 5a).

Complex demodulation has been applied to all 30 precipitation series. Fig. 6 plots the phase and amplitude fluctuations in the annual cycle at all 30 sites. It covers the period from 1800 to the present. In order to facilitate plotting and to reveal as many details as possible, the amplitude and phase changes have been scaled to zero mean and unit variance. Table 1 tabulates the average phase and amplitude values, of the annual cycle, for each of the 30 series plotted in Fig. 6. Inter-comparison of the group of three long

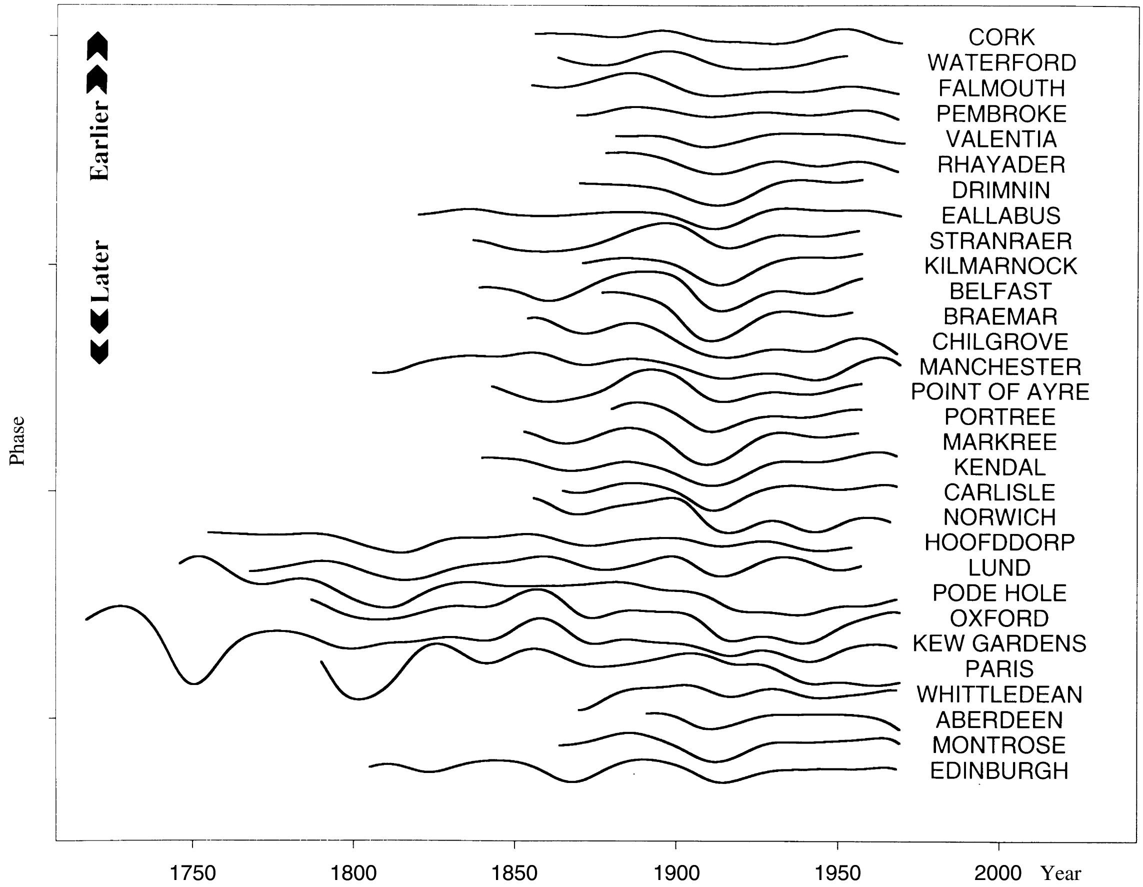

Fig. 7. Phase changes in the annual precipitation cycle. The series are loosely arranged according to their degree of continentality and to their geographical proximity. More oceanic (predominantly winter precipitation) records are placed towards the top of the diagrams, more continental (predominantly summer precipitation) records are placed towards the bottom of the figure. Note the good between-site consistency, especially the lateness of the precipitation seasons in the 1870s and in the first two decades of the twentieth century. Also note how in the 1890s the precipitation season showed a marked earliness.

records from Kew, Pode Hole and Oxford (all from central/south-east England) reveals a number of consistent features. First we can see how the general trends of the phase and amplitude variations are very similar. Secondly note how the phase peaks around the 1840s in all three records, followed by an amplitude peak in the 1850s. Finally note how both the phase and amplitude tend to be high in the 1890s and that the phase drops to a minimum in the 1910s while the amplitude drops to a minimum in the following decade. Similarly the group of records from Portree, Carlisle and Kilmarnock (from around the northern Irish Sea) again show striking similarities with each other but also some differences with the first group. Notice how the amplitude fluctuations slightly lag behind the phase changes at all three of these later sites, but that all six sites show drops in amplitude and phase in the early 1900s.

5.2. Phase

The fluctuations in phase of all 30 records are again plotted in Fig. 7. Here all the records are plotted on the same scales, but offset from each other so that the details of the fluctuations can be seen. Sites have been arranged very roughly according to their geographical position, in order to try to bring out consistent fluctuations. Despite the contrasts between the wet,

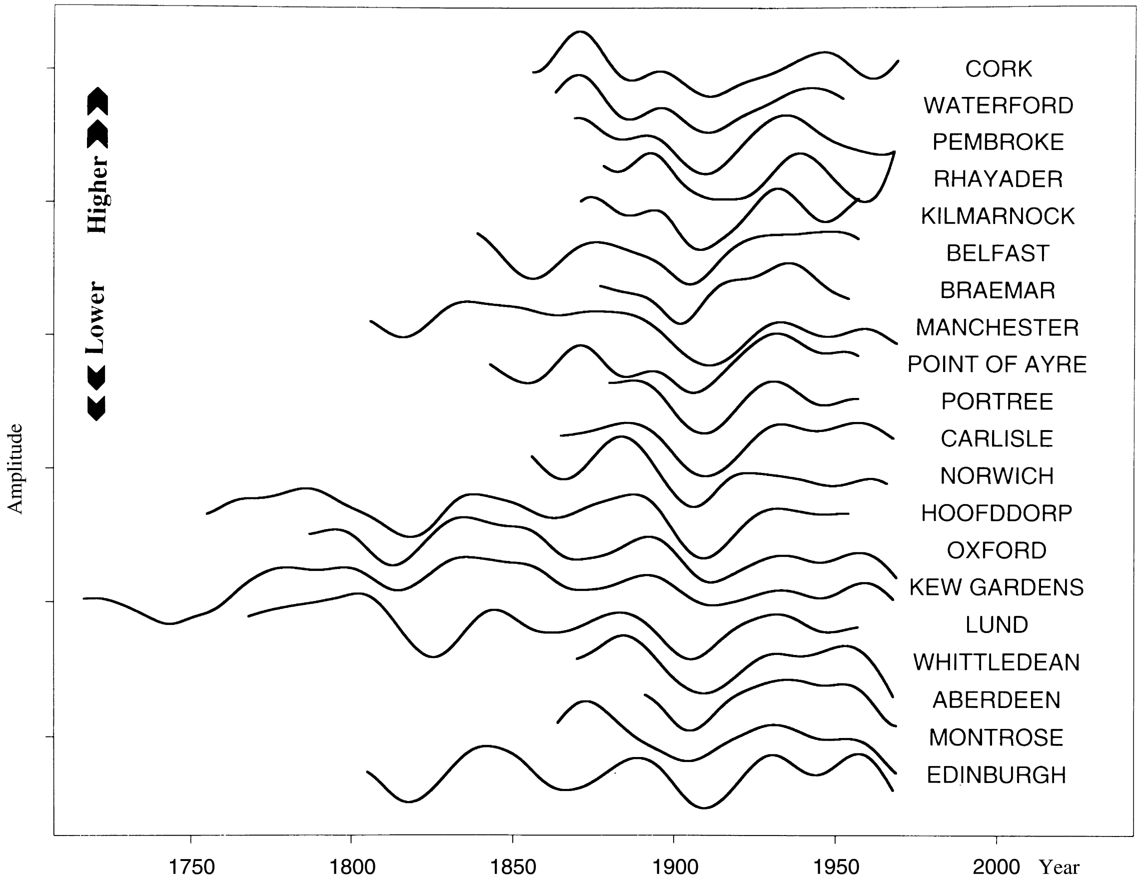

Fig. 8. Variation of the amplitude of the annual precipitation cycle for 20 localities. [Amplitudes scaled to unit variance.] The amplitude changes show less spatial coherence than the phase changes of Fig. 7. Nevertheless decades of high seasonal amplitude (e.g. the 1890s and the 1930s) contrast with decades of low seasonal variation (e.g. the 1820s and the 1910s).

winter-dominated characteristics of western sites and the dry, summer-rainfall dominance of eastern sites, the phase fluctuations at all 30 series are remarkably consistent. In particular Fig. 7 reveals a consistent dip in all traces in the 1900s and 1910s. The dip corresponds to a lateness of the annual cycle of about six weeks compared with the phase of two decades previously.

Many series show their earliest annual cycles in the mid 1800s. The greatest variation in the phase of the annual precipitation cycle is seen in the 18th and early 19th century parts of the data series. The early changes, at Kew, amount to a 13-week shift. However, also note that: (i) the between-record consistency is lowest in the early segments of these exceptionally long data series. (ii) The amplitude of the annual cycle was rather low in the mid 1700s. (iii) The change in the calendar in 1752 caused in an 11-day shift in the Kew data. The phase of the annual precipitation cycle shows a long-term trend. The mean phase slope for the 30 sites of Fig. 7 averages out at the rainfall season becoming later at a rate of five days per century. However, the standard error on this average phase slope is 4.5 days and so it is only slightly significantly different from zero. Thomson (1995), in his analysis of temperature series, demonstrated that the change to the English calendar in 1752 has not been completely accounted for in climate records based on weekly averages. The resulting apparent 3-day step change in September 1752 dominates the phase variation of the annual temperature cycle. This calendrical effect is much less obvious in the phase of the annual precipitation cycle because the variability is 20 times greater than for temperature.

5.3. Amplitude

The fluctuations in amplitude of the annual precipitation cycle are plotted in Fig. 8. Twenty series have been selected as showing the greatest degree of consistency. Note that amplitude is likely to be less reliably reconstructed than phase because instrumental/site difficulties will alter the absolute amount of precipitation measured. Despite such difficulties many of the amplitude fluctuations once again show remarkable between-site consistency. As an illustration, compare the Edinburgh and Lund records. We see coincident amplitude lows in the 1820s, 1860s, 1910s and a smaller minimum in the 1940s. Once again the Kew and Oxford precipitation series display good coherence. All 20 series display a low amplitude to the annual precipitation cycle in the 1900s. While repeatable decadal long variations are found, the average amplitude slope of the annual precipitation cycle of the 20 records of Fig. 8 is found not to differ significantly from zero.

5.4. Trend and long-term change

As an integral part of the complex demodulation procedure a smoothed precipitation record is reconstructed. The trend and long-term changes of precipitation show much less between series consistency than do the fluctuations in the annual cycle. Some of the 30 series reveal slight increases in precipitation with time while others reveal small decreases. The overall impression is of no particular trend to precipitation in Britain during the last 150 years. The 1870s, as noted by Salter and de Carle (1921), tend to be a slightly wetter decade, as did the 1930s. Burt and Shahgedanova (1992) and Jones et al. (1997a,b) have described the history of droughts in England and Wales. The most severe droughts (lasting over eight months) were in 1921 and 1975/1976. In addition somewhat drier conditions prevailed for a couple of decades around the turn of the century. These decadal averages depart by just 5–10% from the mean, a rather small change compared with the overall variability of rainfall. For the 30 sites analysed here, recent changes in the amount of precipitation do not stand out particularly from the natural variability of the last two centuries.

6. Discussion

Temporal changes in the seasonality of precipitation have been shown here to display a reasonable degree of spatial coherence over an area of around $10^6\ km^2$. Even better spatial coherence is found for changes in the seasonality of temperature. Thompson (1995 and unpublished calculations) and Treacy (1996) find excellent spatial coherence between 22 records of air-temperature seasonality throughout the geographic region bounded by Aberdeen, St. Petersberg, Bucharest and Milan. Despite such high spatial coherences there is surprisingly little similarity between the past behaviours of the annual precipitation and temperature cycles. The phase of the precipitation cycle and the amplitude of the temperature cycle are both a consequence of the degree of continentality of the climate and so might be expected to reveal similar temporal behaviour. Nevertheless there are few similarities between the behaviour of these two elements of climatic change on decadal time scales. The most noticeable coincidence of climatic behaviour, as determined by complex demodulation, is between the amplitude of the temperature cycle and the north-south pressure gradient across Europe. The stronger-than-usual pressure gradient in the 1920s and 1990s (e.g. Jones et al., 1997a,b), associated with a more zonal climate system, matches with a more oceanic temperature regime, lower-amplitude annual-temperature cycles and a slightly later precipitation season.

Thomson (1995) reports a pronounced change, around 1940, to more negative phase slopes for the annual temperature cycle. He attributes this acceleration to the effect of increasing greenhouse gases. In this study no changes in the phase slopes of either the annual precipitation or temperature cycles are found. A *t*-test reveals no significant difference, at the 95% confidence level, in the pre-1940 and post-1940 mean phase-slopes for either the 30 British precipitation series or the 22 European temperature records. Although the characteristics of precipitation and the annual precipitation cycle have changed in recent years (e.g. Førland et al., 1996; Mayes, 1996), in a manner not unlike that suggested by a number of CO_2-enhanced climate models, the magnitude of the observed changes in seasonality is well within the limits of variation of "natural" precipitation as observed over the last 300 years.

7. Conclusions

1. The phase (earliness/lateness) of the decadal averages of the annual precipitation cycle has varied by up to 13 weeks, at some sites, during the last 300 years.
2. The amplitude of the decadal averages of the annual precipitation cycle has varied by up to a factor of three during the last 300 years.
3. Excellent spatial coherence of the fluctuations in the phase of the decadal averages of the annual precipitation cycle is found across the whole of Britain and its neighbouring areas.
4. All the data series analysed display a marked lateness of the precipitation cycle in the 1910s.
5. No long-term trend in precipitation amount or in the amplitude of the yearly precipitation cycle is observed.
6. The phase slope of the yearly precipitation cycle is, on average, negative. This slight phase trend to more precipitation falling in the winter half of the year corresponds to the decrease in amplitude of the annual air-temperature cycle, as both reflect a trend to a more oceanic climate during the last two centuries.

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