Dynamical Climatology

Simulation of observed time series of temperature and precipitation over eastern England.

by

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DCTN 11

November 1984

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Abstract

Time series of temperature and precipitation from a 3 year integration of a 5-level general circulation model (Corby et al, 1977) by the Dynamical Climatology branch of the UK Meteorological Office are studied. These are used to establish, and criticise, the ability of the model to simulate some aspects of the observed climate in a single grid box of the model (the eastern England grid box). Problems concerning the comparison of time series of model data with time series compiled from meteorological observations are discussed and some techniques for overcoming these problems developed.

1. Introduction

In recent years much effort has been given to demonstrating the ability of general circulation models to produce a realistic climate. Much of this effort has been concentrated on the comparison of time-meaned global fields and time-meaned zonally-averaged fields with equivalent observed fields (e.g. Manabe and Hahn, 1981; Mitchell, 1981). If we define climate as 'the complete statistical description of the internal climate system ....' (Gates, 1981) it can be seen that these time means give only a limited description of climate, containing no information about the variance of climate states on periods shorter than that of the means. Certainly the impact of climate may depend on the variance of climate on shorter time scales than the monthly or seasonal means often studied. Here an attempt is made to compare with observed data the behaviour in time, on a daily scale, of temperature and precipitation at a single grid box in a 3 year integration of a general circulation model.

To achieve this a combination of simple statistical analyses and direct comparison is used. There are difficulties with parametric statistical tests in cases like these; for example to apply statistical tests to make inferences about a sample from a population, the members of the sample should be independent. In this work some attempt is made to gather information about both the distribution of the data and the length of time between independent members (Mitchell, 1980).

2. Data

The UK Meteorological Office 5-level general circulation model (Corby et al, 1977) modified mainly in the treatment of radiation and land surface processes has been integrated through a multi-annual cycle as described by Slingo (1982) and Mitchell (1983). This integration was used to supply the model time series which were approximately 1100 days long starting at model day 100. These series are of daily values of temperature and precipitation from the eastern England grid box which is approximately 330 km square and centred near Cambridge (Fig. 1). In the model this grid box has a height above sea level of 101 m whilst the grid box immediately to the west (Wales and Ireland) has a height above sea level of 311 m.

The model has pressure divided by surface pressure (σ) as a vertical co-ordinate and for temperature instantaneous values at midnight at $\sigma = .9$ and at the surface were taken, with the $\sigma = .9$ data being used primarily. For precipitation daily accumulated values retrieved at midnight were taken.

For the real temperature data a daily version of the Central England Temperature (CET) time series is chosen (Storey, 1981), this consists of values meaned over 6 stations. The values are an average of the daily maximum and minimum screen temperature (at a height above ground of 1.5 m). A number of slightly overlapping 1100 day time series starting at 1st January 1959, 1st January 1962, 1st January 1965, 1st January 1968 and 1st January 1971 are used.

There are a number of differences between the data sets under comparison which may be significant. For both precipitation and temperature an attempt is being made to compare what is essentially an area-meaned set of values (grid point data being defined to be the value throughout the grid box area) with the mean of a number of individual observations. As the number of representative stations chosen for comparison increases, the approximation to the area mean will improve; hence, ideally, the maximum number of available, representative, stations from within the grid box area should be used. However not all such stations are necessarily representative (Manley, 1974; Storey, 1981); for example stations may be located in frost hollows, rain shadows, or in areas of orographically induced precipitation.

Precipitation has little spatial coherence and its distribution is highly skewed; hence more stations are needed to represent the area mean and as the number of stations increases the skewness will decrease, i.e. the 'shape' of the distribution of real precipitation depends on the number of stations used in the mean. By using time series constructed from the means of differing numbers of stations it may be possible to distinguish real differences between model and real data from those generated by the number of stations chosen. To achieve this 3 different time series of daily precipitation totals are chosen.

1. 1100 consecutive days from a single reporting station, Kew. This station's location is shown in Fig. 1.

2. 1100 consecutive days from the mean of six stations, Birmingham, Cambridge, Hastings, Kew, Nottingham, and Oxford. The locations of these stations are shown in Fig. 1. This time series will be referred to as 'The long period stations'.

3. 1100 consecutive days from the mean of 144 stations in England and Wales, but not all in the grid box area, which will be called 'England and Wales rainfall'

Temperature has greater spatial coherence than precipitation and its distribution is far less skewed; hence the choice of the number of stations to represent the grid box area is less critical. To compare a surface midnight temperature from the model with a CET would be inappropriate because of the difference in the impact of radiative effects in the two cases. By using temperatures at $\sigma = .9$ in the model this problem is alleviated since the diurnal cycle in temperature is much smaller at this level; other problems are introduced but these are more systematic and easier to handle. Some results from a time series of surface temperatures (instantaneous daily values at midnight) in the model are included to support conclusions based on the time series at $\sigma = .9$.

3. Results of the temperature comparisons

a) Qualitative

Figs. 2 and 3 show time series for both sets of temperature data, the real time series starting 1st January 1971. The time series in Fig. 3 have the annual and semi-annual cycles removed by a discrete Fourier transform (Temperton, 1976). Both time series have a clearly dominant seasonal cycle with a large number of shorter time scale features superimposed. From Fig. 3(a) it can be seen that short time scale features of the model time series vary with season with an apparent increase in the variance, on a time scale of several days, during the winter months. Closer inspection shows that this is largely due to a number of intense cold periods which occur during the model winter. Fig. 3(b) shows the comparable time series for the surface temperatures from the model; this also displays those features. This behaviour is only weakly evident in the real data.

Each of the model winters is looked at again, in more detail, in Fig. 4, where time series of temperature and of U and V wind components at σ = .9 are shown, U positive from the west, V positive from the south. In each of the three model winters the most intense cold spell is associated with a change in sign of the U wind component whilst the V component shows little systematic correlation with temperature. Fig. 5 shows limited area daily charts for temperature at σ = .9 and mean sea level pressure for the period of the most intense cold spell during the second model winter. At day 640 there is a string of depressions across the north Atlantic extending into Europe with a strong westerly flow covering the United Kingdom and a ridge in the temperature field over the eastern Atlantic. By day 641 a more intense depression has moved to the southwest of Iceland and in the following 2 days appears to transfer in a southeasterly direction across the United Kingdom. This produces an outbreak of easterly winds at $\sigma = .9$ across much of Europe. On the maps the spread of cold air across the area can be clearly seen.

b) Statistical Analysis of Time Series

Table 1 shows means and standard deviations for all the time series used, including one of surface temperatures from the model, and for a 10 year period (1961-1970) of temperatures both at screen height and at 900 mb for the radiosonde stations at Crawley and Hemsby (Meteorological Office, 1980). Both these stations are within the grid box area (Fig. 1). The 900 mb values are calculated from midnight ascents whilst the screen values are based on a mean of midnight and midday values. The amplitudes of the annual cycles at Hemsby and Crawley were estimated from the difference in temperature between the hottest and coldest month in the year. Table 2 shows the means and standard deviations, where the annual and semi-annual cycles have been removed, for the model at the surface and at 900 mb and for all the CET time series.

Temperature statistics from Crawley and Hemsby can be used to help to distinguish those differences which are due to the comparison of screen values with values at $\sigma = .9$ from those differences due to a failure of the model to produce a realistic time series of temperature.

i) Means

Since the model data are from $\sigma = .9$, or the surface, at midnight and the C.E.T. data is at screen height and a mean of maximum and minimum values a direct comparison of the different types of time mean should not be made. Data from Crawley and Hemsby are used to circumvent this problem.

Given the temperature in the model at $\sigma = .9$ it is possible to approximate the time mean model temperature at 900 mb. The mean surface pressure, calculated from daily instantaneous values at midnight, for the eastern England grid box for 1090 days starting at model day 100 is 994.5 giving a mean pressure at $\sigma = .9$ of 895.05. If the time meaned change of temperature with pressure is similar to that for an I.C.A.O. standard dry atmosphere (International Civil Aviation Organisation) then the time meaned differences in temperature between $\sigma = .9$ and 900 mb will be approximately 0.3K. This gives, from Table 1, a time meaned model temperature of 4.4 °C at 900 mb at midnight which is .3K lower than the 900 mb midnight temperature for Crawley and Hemsby. Hence the model appears to be slightly too cold at 900 mb. (This calculation assumes that the temperature lapse rate and change in pressure at $\sigma = .9$ are independent).

From Table 1 the mean temperature of the mean of the 5 C.E.T. time series is 9.4 °C whilst the mean surface temperature of the model time series is 3.8 °C. To compare these means use is again made of the temperatures from Crawley and Hemsby. The average of the midnight and midday temperatures from Crawley and Hemsby, at screen height, is 9.5 °C, close to the 9.4 °C for the C.E.T. time series. Hence, since the model time series have midnight values these are compared with the midnight values, at screen height, from Crawley and Hemsby which over the 10 years are 7.7 °C and 8.0 °C respectively, about 4K higher than the model value. However, the model value is for the surface and a comparison of screen and grass minimum temperatures suggest the surface may be typically 2K colder than the air at screen height indicating that real midnight surface temperature is about 6°C. This is still warmer than the model value by about 2K.

ii) The annual cycle and standard deviations

The amplitudes of the annual cycle are also shown in Table 1, the model having a smaller annual cycle than the C.E.T. time series. Part of this discrepancy occurs because the annual range of night time temperatures is less than the annual range of mean temperatures, due to the larger diurnal variation in summer. Figs 6 and 7 show histograms of real and model temperatures; the histogram of the C.E.T. time series has a flatter and broader distribution. However, when the annual and semi-annual cycles are removed much of this difference disappears. The histograms are now very similar but with a longer cold tail in the model distribution.

Table 1 shows the standard deviations for all the cases; the model value at $\sigma = .9$ is far lower than any of the comparison values, and in particular is lower than the values for Crawley and Hemsby at 900 mb. The standard deviation for the model surface temperature is much closer to the observed values and in particular is very close to the mean of the C.E.T. standard deviation which is 5.3 K. However Table 2 shows that with the annual and semi-annual cycles removed the standard deviation in the model at both $\sigma = .9$ and at the surface is higher than that for the CET time series.

Although the mean difference in height between the 900 mb surface and the $\sigma = .9$ surface is small (see previous section) the height of the 900 mb surface depends on surface pressure. The effect of moisture content on the height of pressure and sigma surfaces is small. The most important influence on the height of a sigma surface is the temperature of the air below that surface. For example, a major change in air mass type over the surface of the eastern England grid box may produce a change of 10°C in the temperature of the lowest sigma layer in the atmosphere. This would cause a change of approximately 30 m in the height of the $\sigma = .9$ surface. Changes in elevation of 900 mb surface may be much larger. For example, if a major depression crosses the grid box area surface pressure may change from 1000 to 950 mb; with no change in the temperature of the air below the 900 mb surface a change in height of the 900 mb surface of about 300 m would occur, an order of magnitude greater than the change in height of the sigma surface from a 10° change in air temperature. Since temperature normally decreases with increasing height this indicates that the variance of temperature at 900 mb should be greater than that at $\sigma = .9$ (this effect will be modified by correlations between surface pressure and temperatures at 900 mb a positive correlation reducing the variances at 900 mb). It would therefore be incorrect to state from the evidence here that the standard deviation of the model temperature at $\sigma = .9$ was too low from a comparison with the higher values seen for Crawley and Hemsby at 900 mb.

Another factor which may cause the standard deviation to be higher at Hemsby and Crawley than in the model is the effect of the annual cycle on the data. Table 1 shows that the annual cycles in the CET time series are larger than in the model data. When the annual and semi-annual cycles are removed, the model both at $\sigma = .9$ and at the surface has a higher standard deviation than the CET time series (Table 2) which may be due to the impact of the periods of intense cold during the model winters.

iii) Power spectral densities and autocorrelations

Power spectral densities were produced by a maximum entropy method (Lacoss, 1971) as described by Ross (1975). The technique used approximates the time series by an autoregressive process and finds the power spectrum of that process (Ulrych and Bishop, 1975). The user of the technique can choose the order of the autoregressive process, and details of the power spectral densities depend on this choice. However, for a wide range of orders the shape of the log of power spectral density for both the real and model time series does not change.

Box and Jenkins (1976) show that for an autoregressive process

$$\tilde{Z}_t = \sum_{i=1}^{\ell} \phi_i \tilde{Z}_{t-i} + a_t$$

where $\tilde{Z}_t = Z_t - \mu$ (μ is the mean of the process), the a_t's form a white noise process, and ℓ is the order of the process then the power spectral density can be written as

$$P(f) = \frac{2\sigma_a^2}{\left|1 - \sum_{K=1}^{\ell} \phi_K e^{-i2K\pi f}\right|} \quad 0 \leqslant f \leqslant 1/2$$

If $0 < \phi_1 < 1$ this leads to a simple power spectral density for a first order process an example of which is shown in Fig. 8.

Fig. 9 shows the logarithm of power spectral density for one of the C.E.T. time series and for the model time series (both with annual and semi-annual cycles removed). Considering the broad trend the logarithm of power spectral density for the Central England

Temperatures has a shape close to the theoretical one for a first-order autoregressive process (Fig. 8) except at very low frequencies where the time series has less power than in the theoretical case. The model temperatures fit the theoretical shape less well having more power than the Central England Temperatures between $2\Delta tf = .5$ and $2\Delta tf = .2$ (4 day and 10 day waves). This is a similar time scale to that of the cold periods during the model winters and may reflect their influence on the power spectrum.

If $0 < \phi_1 < 1$ this approach leads to a very simple formulation for the autocorrelation function as an exponential decay where ρ_K is the correlation at lag k and $\rho_K = e^{-\nu|k|}$. Based on this formulation Leith (1973) showed how a characteristic time between effectively independent sample members could be calculated to be $T_o = 2/\nu$. The correlation at a lag of 1 day was used to give an estimate for ν and hence for T_o. For the model time series this gives a time between effectively independent members of approximately 7 days and for the CET time series of between 4 and 7 days for differing 1100 day periods. The autocorrelograms for the model and one of the CET time series (Fig. 10) show reasonable agreement with this, both having correlations near zero by day 7.

iv) Goodness of fit

The Chi-square goodness of fit test (Mann and Wald, 1942) can be used to test sample distributions for normality by comparing them with a normal distribution. The greater the difference between the two distributions the higher the value of the test statistic. Choosing the number of class intervals by the method described by Mann and Wald for the 10% level of significance gives 65 degrees of freedom and a critical value of 79.96, ie for a normal sample the value of the test statistic would exceed 79.96 on only 10% of occasions. For the model time series with annual and semi-annual cycles removed the value of the test statistic was 99.4 allowing the rejection of the null hypothesis that this sample is from a normal population. The 1100 day period of C.E.T. starting 1st January 1971 was used as a comparison data set; this gave a test statistic of 59.34, and the null hypothesis, that the sample is from a normal distribution, cannot be rejected. This quantitative comparison of the model and real data highlights the differences between the two distributions. To calculate the test statistic the difference between the number of members from the observed distribution and the expected number from the theoretical distribution in each class interval is calculated. The larger the difference, the greater the distance of the observed distribution from the theoretical one in that class interval. The largest single difference in either the real or observed data is in the first class interval for the model data, i.e. that interval affected by the long cold tail observed in the model data.

c) Summary

An attempt has been made to use CET time series to compare model and real data in the area of the eastern England grid box. Difficulties were encountered due to the differences in the observation types used from the model and from reality, temperature data from Crawley and Hemsby were used to overcome this problem. It was then found that the model was too cold at the surface and slightly too cold at 900 mb. Although it was still difficult to compare standard deviations, with the annual and semi-annual cycles removed the model standard deviation was higher. Examination of the time series suggested that this may have been due to outbreaks of cold easterly winds which occur in this area during the model winters.

A Chi-square goodness of fit test showed the CET data to have a better fit to a normal distribution than the model data, further investigation indicated that this was also due to the cold easterlies during the model winters. Some evidence of the impact of these cold outbreaks came from the power spectra, the model having greater power than the real data in waves with periods of between 4 and 10 days. Power spectra for the model and real data were similar with both having characteristics associated with a red noise process except at low frequencies where they had too little power. Assuming both time series could be modelled by a red noise process estimates of the time between effectively independent members were made giving 7 days for the model time series and between 7 and 10 days for the CET time series.

4. Results of the precipitation comparison

a) Qualitative

Fig. 11 shows the precipitation values for the three real time series and for the model time series. Clearly the model time series has a different character from the other 3 and though the real cases are different from each other there are a number of consistent differences between the model and real time series. In particular there are far fewer dry days in the model time series (Table 3) and as can be seen from Fig. 11 dry spells in the model are much less frequent and of shorter duration.

The lowest precipitation level measured by the rain gauges used in the real data is 0.05 mm with values of 0.05 and above being recorded as 0.1 whilst values below 0.05 (a trace) are recorded as zero. Because of this, the number of dry days recorded in the real time series are an overestimate of the number of days with no precipitation occurring. In the case of a single station 0.05 mm is the lowest recordable precipitation whilst for the long period stations, a mean of 6 rain gauges, 0.017 mm is the lowest recordable precipitation. Numerical constraints restrict the lowest recordable precipitation from the England and Wales rainfall to 0.09 mm. To improve the comparison of numbers of dry days the definition of a dry day in the model was varied so that a day with less precipitation than could be recorded in the comparison data was defined as dry. This gave 118, 84, and 142 dry days for cut off values of 0.05, 0.009 and 0.09 mm and 37 dry days for a cut off value of 0.09 for the grid box to the west. These figures are still all lower than the number of observed dry days.

b) Statistical Analysis of time series

i) Means

Table 3 shows that the mean value of the model precipitation is much higher than that of the long period stations and the single station and slightly higher than that of the England and Wales rainfall. However not all the stations in the England and Wales data set lie within the grid box area, some being within the adjacent grid box to the west for which data are also given in Table 3. The England and Wales rainfall has a much lower mean precipitation than the average of the eastern England grid box and the grid box to the west combined.

ii) Deviations

Table 3 shows that the variance of the model rainfall lies within the range of those for the comparison data sets.

The inability of the model to produce days with exceptionally high rainfall is shown in Fig. 12 which shows all the days both for the model and for 3 consecutive 1100 day periods for each of the comparison data sets in which precipitation totals exceed 15 mm. The eastern England grid box has more events in the 15-17.5 mm range than any of the real data sets but otherwise very few events and none with daily precipitation above 20 mm. In the most similar of the real cases, the 3rd 1100 day period for the long period stations, there are still 3 days with greater precipitation than on the wettest model day.

The England and Wales rainfall contains some stations from the area of the grid box to the west of the eastern England grid box. This grid box has a much longer Atlantic coast than the eastern England grid box and far more days with high precipitation totals. The grid box to the west has more wet days than both the eastern England grid box and the England and Wales rainfall. However for 2 of the 3 periods the England and Wales rainfall has a higher maximum value of precipitation. Since the grid box to the west has a much higher mean value of precipitation than either the England and Wales rainfall or the eastern England grid box this is additional evidence that the model is poor at producing days of exceptionally heavy precipitation.

(iii) Power spectral densities and autocorrelations

Figs. 13, 14 and 15 show the logarithm of the power spectral density, the power spectral density, and the autocorrelograms for the model and for the England and Wales rainfall. The other comparison rainfall data give similar results to those for the England and Wales rainfall. The logarithm of power spectral density for the England and Wales rainfall has approximately the form associated with a red-noise model but with a much shallower gradient than for temperature indicating that precipitation could be modelled by a 'whiter' process than temperature. The logarithm of the power spectral density for the model time series shows little concentration of power in the lowest frequencies and examination of the power spectral density (Fig. 14) shows the maximum power occurring in frequencies in the range $2\Delta tf = .5$ to $2\Delta tf = .2$ (4 days to 10 days). This is the same frequency range for which the model temperatures had more power than the Central England Temperatures.

These data do not fit the theoretical model used in the approximation of the time between effectively independent members as well as do the temperature time series. Nevertheless the estimate may give an idea of the time between independent members, all the rainfall time series giving values between 1 and 2 days indicating that both in the model and in reality precipitation time series have much shorter memories than temperature time series. The autocorrelograms are consistent with this though in all the real cases they show correlation falling more slowly than for the model time series.

iv) The logarithm of precipitation

So far the comparison of precipitation has concentrated on the extreme values which daily precipitation takes (i.e. on days on which no precipitation occurs or when high levels of precipitation occur). The further study of the distribution of precipitation is hampered by its extreme skewness. However, by separating the time series into dry and wet days, dry days being defined as those with no precipitation occurring, a good deal of the skewness can be removed from the distribution by performing a logarithmic transformation of the data (Katz, 1982).

Fig. 16 shows the distribution in the four cases in the logarithmic transformation mode. The range of the histograms in the real cases is restricted by the accuracy to which real rainfall data are available and hence Fig. 16 only shows those days with precipitation greater than 1 mm. Table 4 shows the minimum level of precipitation recorded in the various cases. The distribution of model rainfall is very similar to that shown by Katz (1982) from a control integration of the Oregon State University G.C.M. The model distribution has a peak where the precipitation is about 5 mm. The peak is not apparent in either the single station data or the England and Wales rainfall data; there is a slight peak at lower levels in the long period stations data. Although the model has lower maximum values of precipitation it does have a larger proportion of its distribution at the upper end of the histogram (precipitation greater than 5 mm) than the real cases.

v) Goodness of fit

As in the comparison of temperature a Chi-square goodness of fit test is used. The distribution of precipitation with dry days included, both in the model and for the real cases, is clearly not normal and this is highlighted by the very large values of the test statistics produced. For the 2.5% level of significance with 55 degrees of freedom the critical value of the test statistic is 77.36,. ie. for a normal sample the value of the test statistic would exceed 77.36 on only 2.5% of occasions. For the model time series the value of the test statistic was 1980.53. This especially reflects the major impact of dry days on the distribution.

The Chi-square goodness of fit test is also used on the distribution of the log of rainfall on wet days. For the 2.5% level of significance with 53 degrees of freedom the critical value of the test statistic is 74.98; for the model time series the value of the test statistic is 343.08. Hence with the dry days removed and after a logarithmic transformation the model precipitation is still clearly not normally distributed. Unfortunately this test cannot sensibly be used on the log of the real data because of the limited accuracy to which the real rainfall data are available.

5. Conclusions

This work has attempted to assess some aspects of the model's ability to reproduce the observed climate which have previously received little attention. In particular the variation of climate parameters (temperature and precipitation) in time at one location are studied instead of the variation in space at a single time or the variation in space of a time meaned field. Difficulties encountered in carrying out the work have been summarized in the text and it is hoped that the attempts made to surmount them will help in further work of this type being carried out within the Meteorological Office and elsewhere.

Below results of this work are summarized and possible future developments briefly discussed.

a) Results

There are a number of difficulties involved in the comparison of long time series of real and model data in that the data sets may not be strictly comparable. However, knowing what the differences are and what systematic effects on the comparison these differences may make, a study can be made.

The comparison of the temperature data showed that with the annual and semi-annual cycles removed the two data sets have broadly similar statistical properties (Table 2, Figs 6, 7) with the two histograms being very similar. The comparison also highlights the occurrence in the model of a number of intense cold periods, lasting several days with at least one in each winter, in the model.

Only in one of the 5 periods studied is there a cold period of similar intensity to that which occurs in each model winter (in the winter of 1962-1963). The ability of the model to produce periods of intense cold weather over the eastern England grid box is a strength even though the model produces too many of them with too great severity. Here the model is producing an important short time scale feature of climate.

A comparison of the mean model temperature with real values indicated that the model temperature was too low at the surface and possibly also slightly too low at 900 mb. The results for the standard deviations were less clear, though with the annual and semi-annual cycles removed the model appeared to have too high a standard deviation. This may reflect the impact of the intense cold periods in the model's winters on its variance.

The comparison of the precipitation data is a more difficult problem due to the highly skewed distribution of daily precipitation totals. The model fails to produce a realistic distribution of precipitation in several ways. The model fails at both extremes of the distribution with too few dry days and too few extremely wet days. Although this may be explained as being due to increasingly dense sampling reducing the skewness of the distribution, the England and Wales rainfall, a mean of 144 stations, when compared against the two grid boxes, still has higher maximum values (Table 3) and a far higher number of dry days. The mean daily precipitation is too high in the model, and the model has a higher mean value whether or not the dry days are removed from the sample (Table 4). This may be due to the greater proportion of wet days with precipitation greater than 5 mm in the model.

An estimate of the length of time between effectively independent members of the temperature time series gave a value of approximately 7 days for the model and between 4 and 7 days for the CET time series. For precipitation much lower estimates of between 1 and 2 days were obtained though the technique used was less applicable to the precipitation data than to the temperature data and analysis of the autocorrelograms suggested a longer period between effectively independent days for the real rainfall.

b) Possible future developments

In this work, changes between the character of summer and winter periods in the time series of temperature have been noted. Further evidence of seasonal changes in short time scale features of these time series could be gained by separately studying time series of winter and summer values (Katz (1982) shows distributions of both winter and summer daily precipitation totals).

The study of time series of grid boxes located in areas of the world with different climates would add to the knowledge of the model's climatology. For example a time series from both an oceanic environment and a continental environment could be used. However, care would have to be taken to choose areas 'rich' in real data if a useful comparison were to be made.

Acknowledgements

This work was partly supported by the E.E.C. through contract CLI-030-081-UK(H). I am grateful to Dr J F B Mitchell for the help and encouragement given throughout this work and to Dr P R Rowntree for helpful discussion and useful comments on the work. Thanks are also due to Dr C A Wilson for his suggestion on the definition of dry days within the model.

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Table 1 Temperature

	Mean	S.D.	Annual Cycle
CET (1959)	10.0	5.3	6.4
CET (1962)	8.8	5.6	6.9
CET (1965)	9.3	5.0	6.0
CET (1968)	9.4	5.7	7.0
CET (1971)	9.5	4.9	5.9
Model (σ = .9)	4.1	4.2	4.1
Model (Surface)	3.8	5.4	4.9
Hemsby (screen)	9.5	5.9	5.8
Crawley (screen)	9.5	6.2	6.1
Hemsby (900 mb)	4.5	5.8	5.1
Crawley (900 mb)	4.9	5.7	5.0

Means, standard deviations, and the amplitudes of the annual cycles for 1100 day time series for Central England Temperatures, 1090 day time series for the eastern England grid box, and 10 years of daily data for Hemsby and Crawley.

Table 2 Temperature

	Mean	S.D.
CET (1959)	10.0	2.6
CET (1962)	8.8	2.7
CET (1965)	9.3	2.5
CET (1968)	9.4	2.7
CET (1971)	9.5	2.4
Model (σ = .9)	4.1	3.0
Model (Surface)	3.8	3.9

Means and standard deviations for 1100 day time series for Central England Temperatures and 1090 day time series for the eastern England grid box, all with the annual and semi-annual cycles removed.

Table 3 Precipitation

	Mean	Standard Deviation	Max	No. of dry days
England and Wales rainfall rainfall	2.7	3.77	35	156
Long period stations	1.7	3.06	29	340
Single stations	1.4	3.78	48	628
Model (1)	3.2	3.36	19	76
Model (2)	5.5	5.18	32	13

Means, standard deviations, maximum daily values in mm and the number of dry days for a 1100 day period.

Model (1) is the eastern England grid box

Model (2) is the grid box to the west.

Table 4 Precipitation

	Mean	Standard Deviation	Max	Min
England and Wales rainfall rainfall	3.2	3.89	35	0.09
Long period stations	2.4	3.44	29	0.017
Single stations	3.3	5.27	48	0.1
Model (1)	3.4	3.38	19	0.001
Model (2)	5.6	5.17	32	0.001

Means, standard deviations, maximum and minimum daily values in mm. Data have all the dry days removed.

Figure 1

Representation of the U.K. and near continent by the 5-level model.

(Shading indicates sea areas)

B:- Birmingham
C:- Cambridge
H:- Hastings
K:- Kew
N:- Nottingham
O:- Oxford

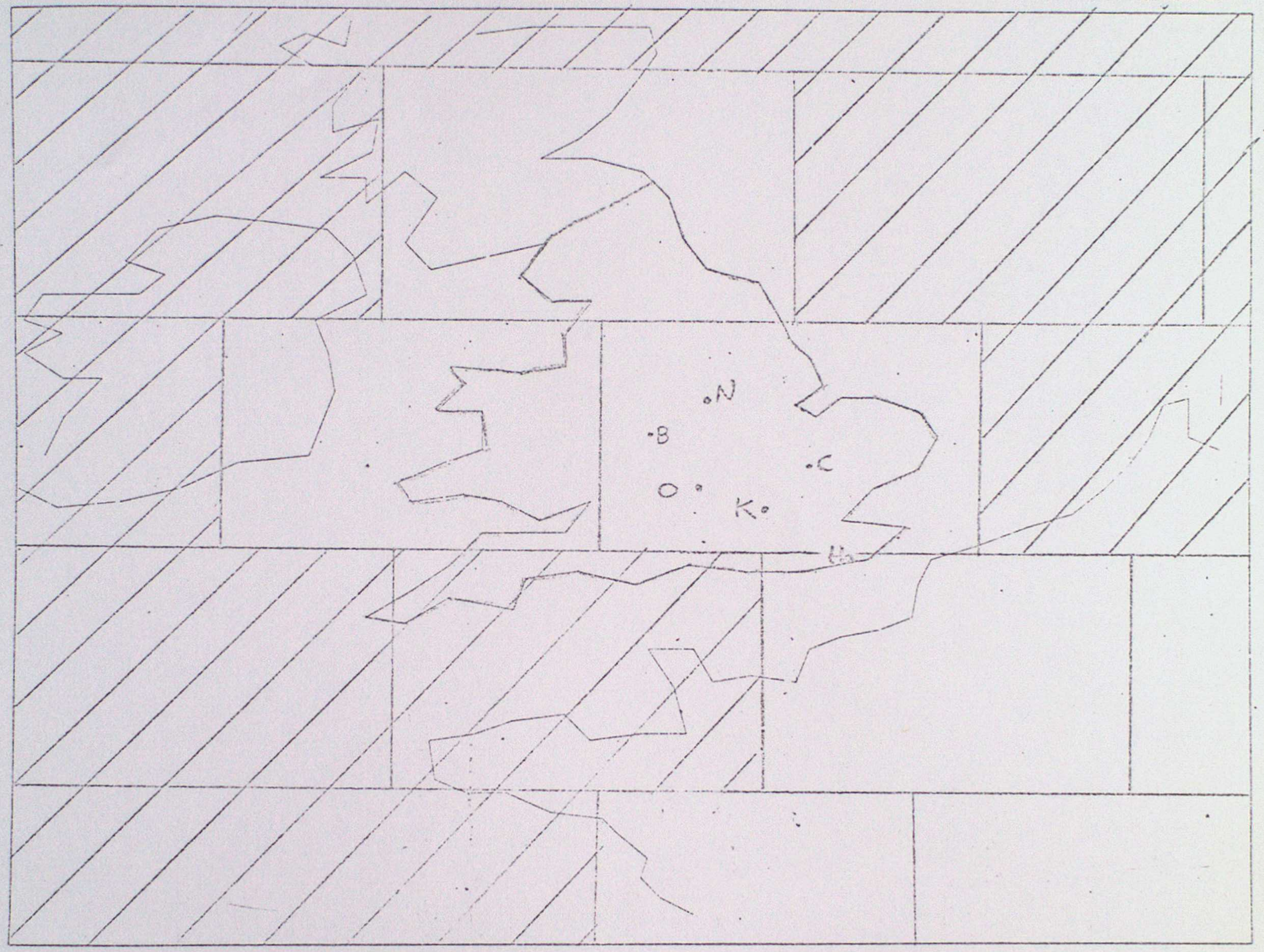
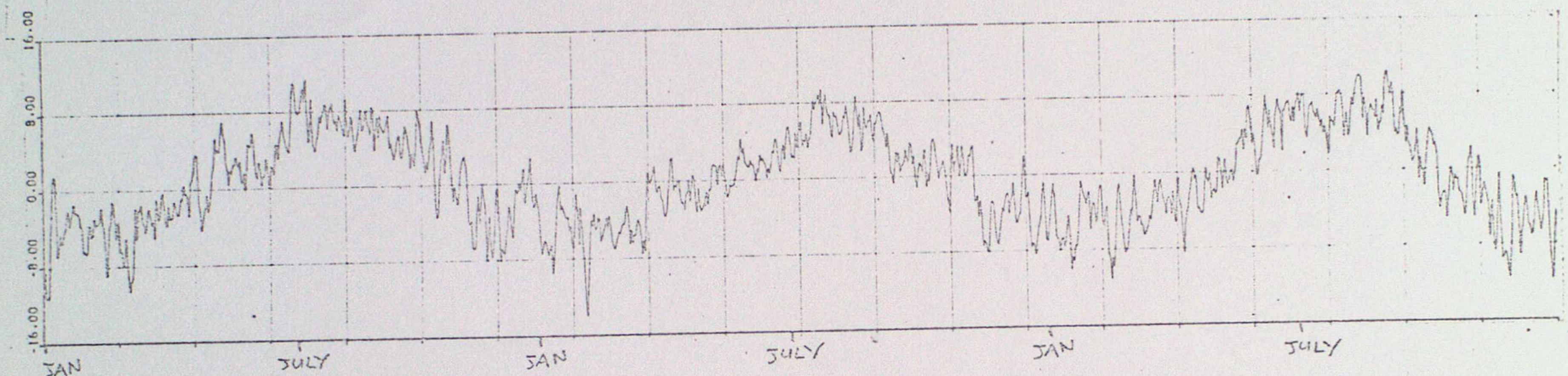


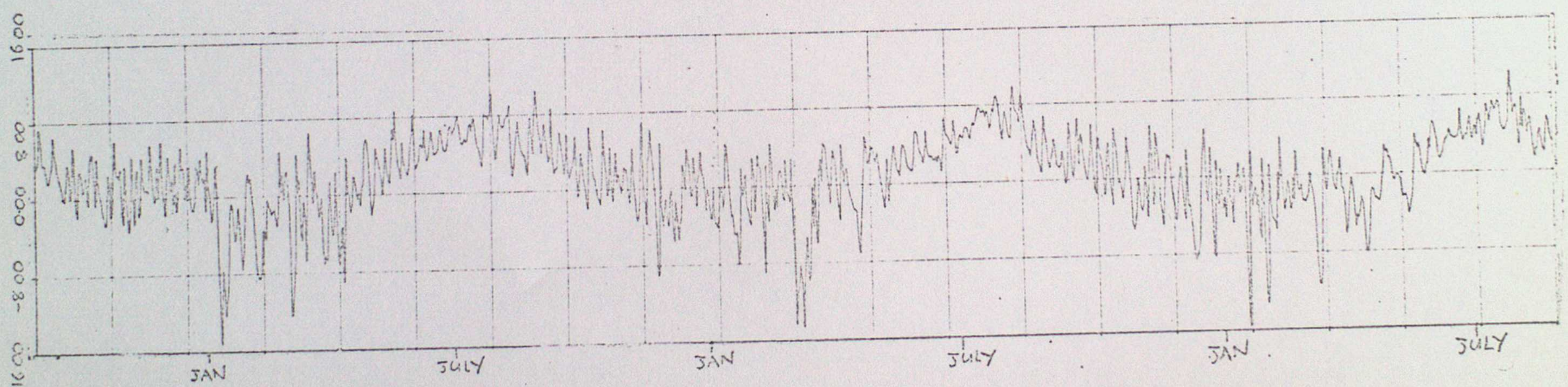
Figure 2(a)

Time series with the trend and mean removed

Vertical axis: °C



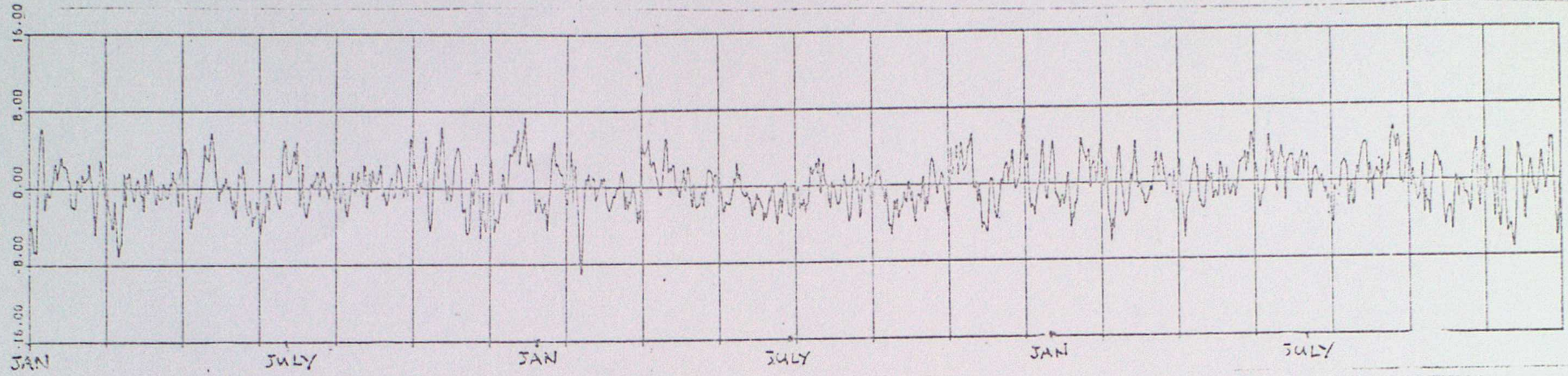
1100 days Central England temperatures starting 1st January 1971



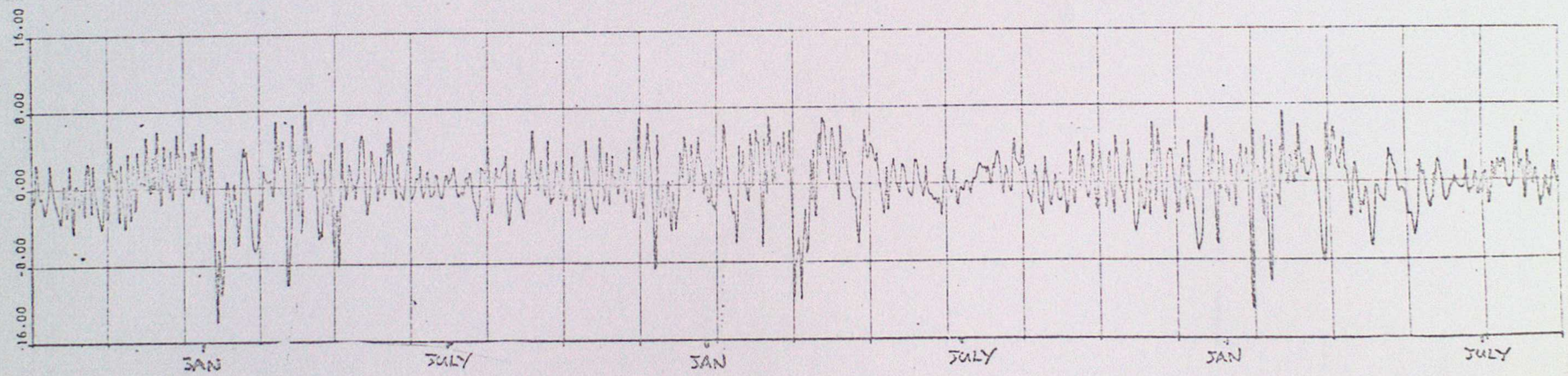
1090 days Model temperatures at $\sigma = .9$ for the eastern England grid box.

Figure 3 (a) Time series with the trend, mean, annual and semi-annual cycles removed

Vertical axis: °C



1100 Days Central England Temperatures starting 1st Jan. 1971

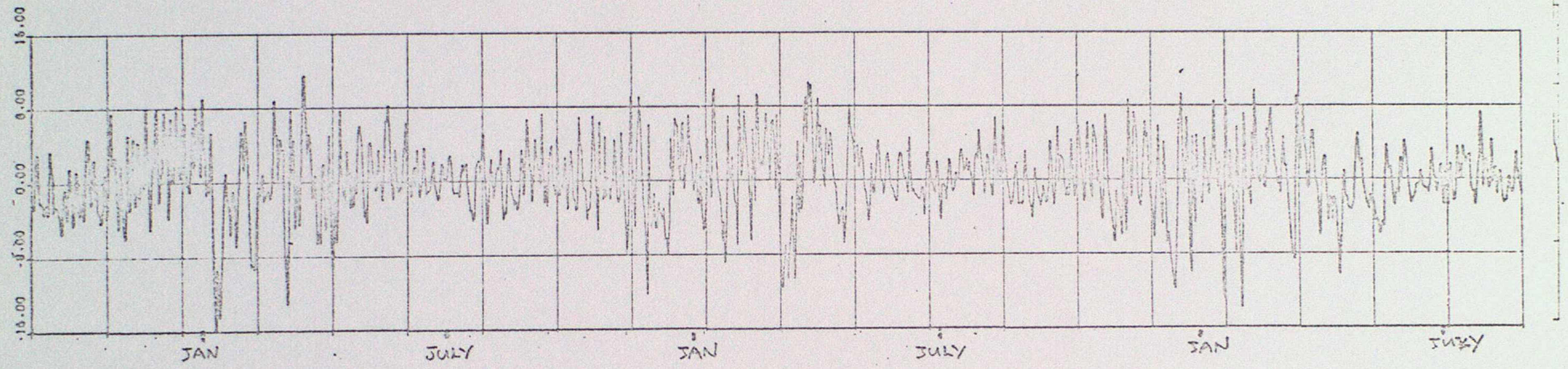


1090 Days Model Temperatures at near 900 mb for the Eastern England Grid Box.

Figure 3(b)

Time series with the trend, mean, annual and semi-annual cycles removed

Vertical axis: °C



1090 days Model temperatures at the surface for the eastern England grid box.

Figure 4(a)

Time series of temperature, U and V wind components at $\sigma = .9$ for the first model winter (dashed lines are V wind component)

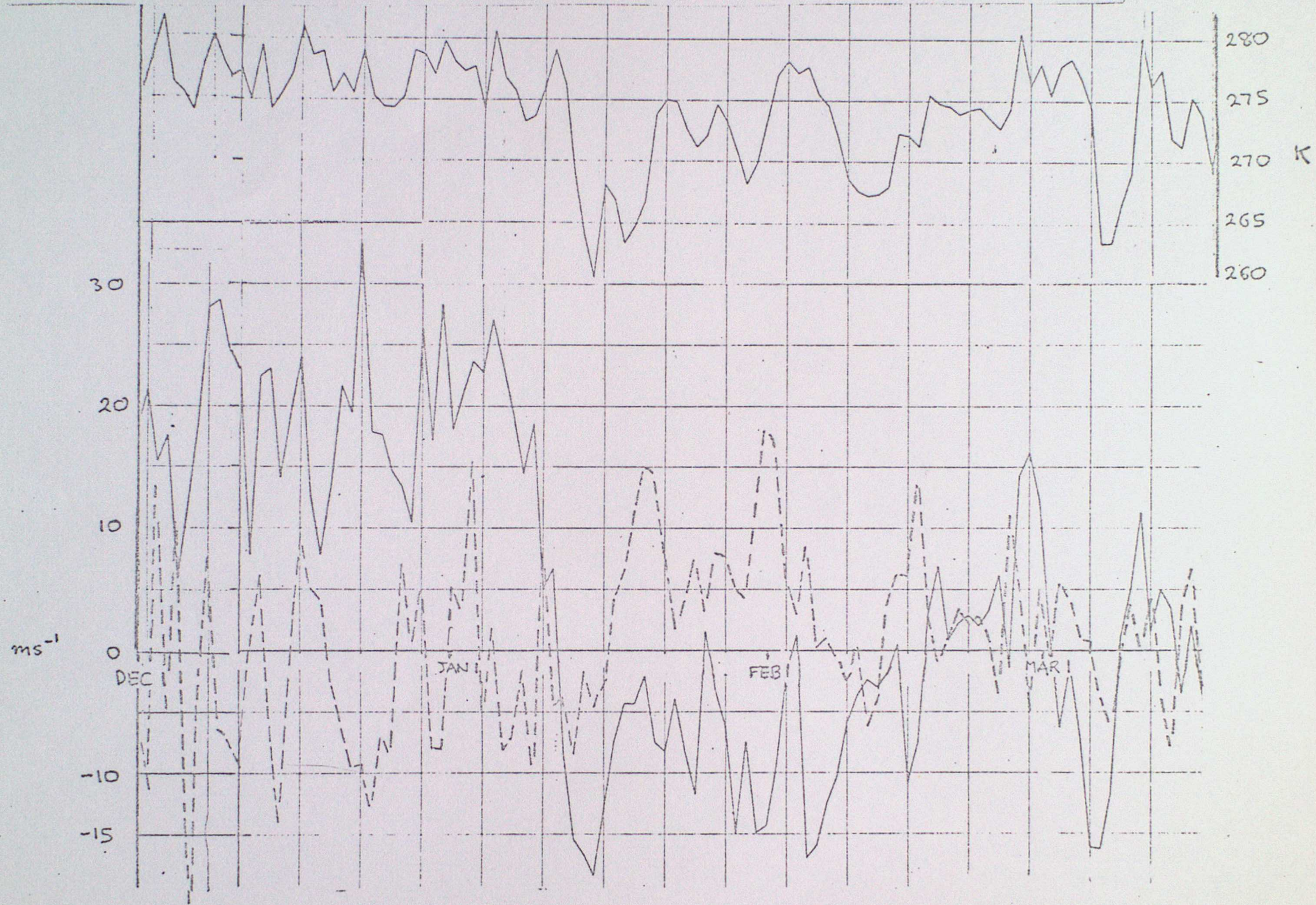


Figure 4(b)

Time series of temperature and U and V wind components at $\sigma = .9$ for the 2nd model winter (dashed lines are V wind components)

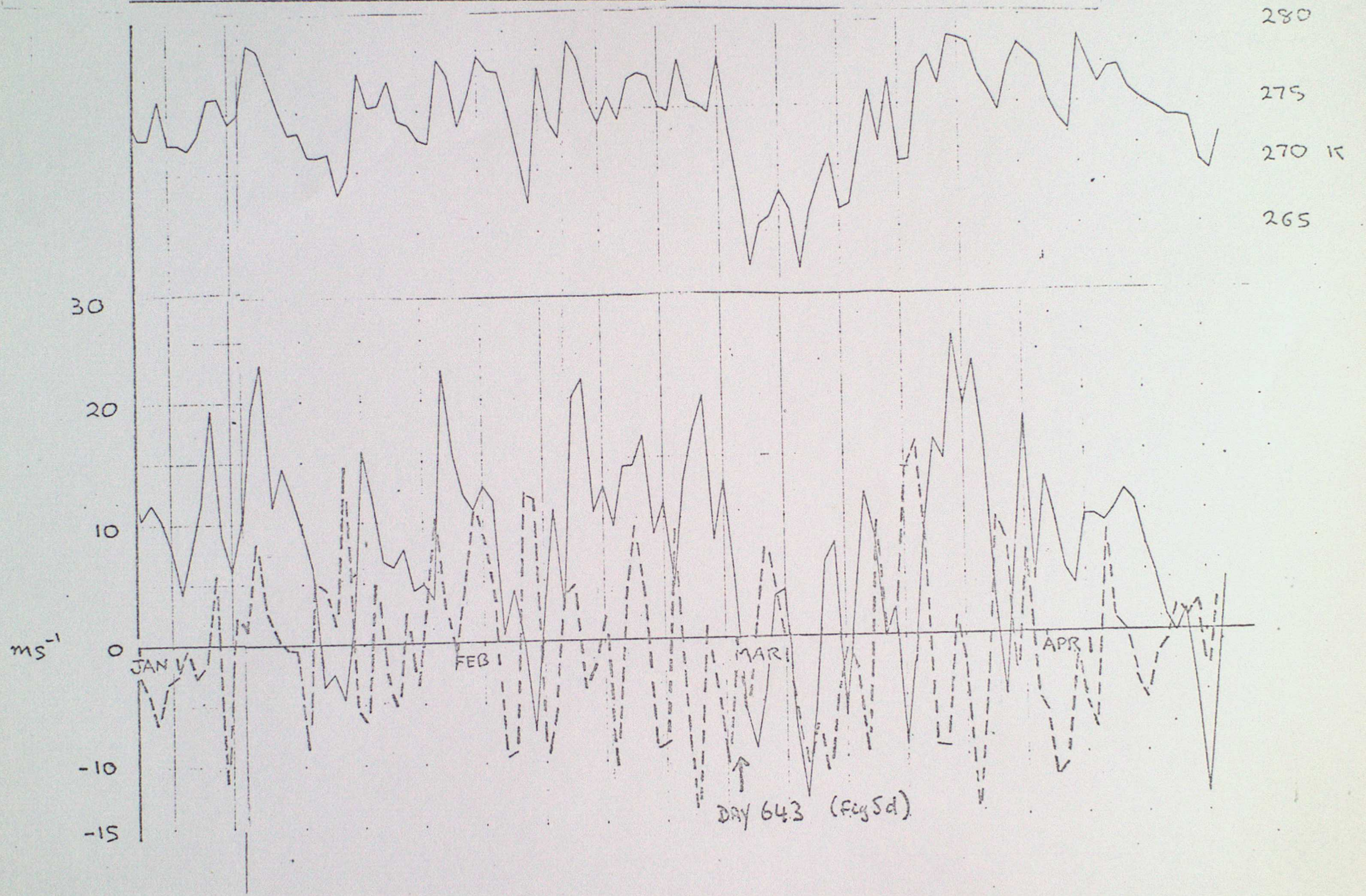


Figure 4(c)

Time series of temperature and U and V wind components at $\sigma = .9$ for the 3rd model winter (dashed lines are V wind components)

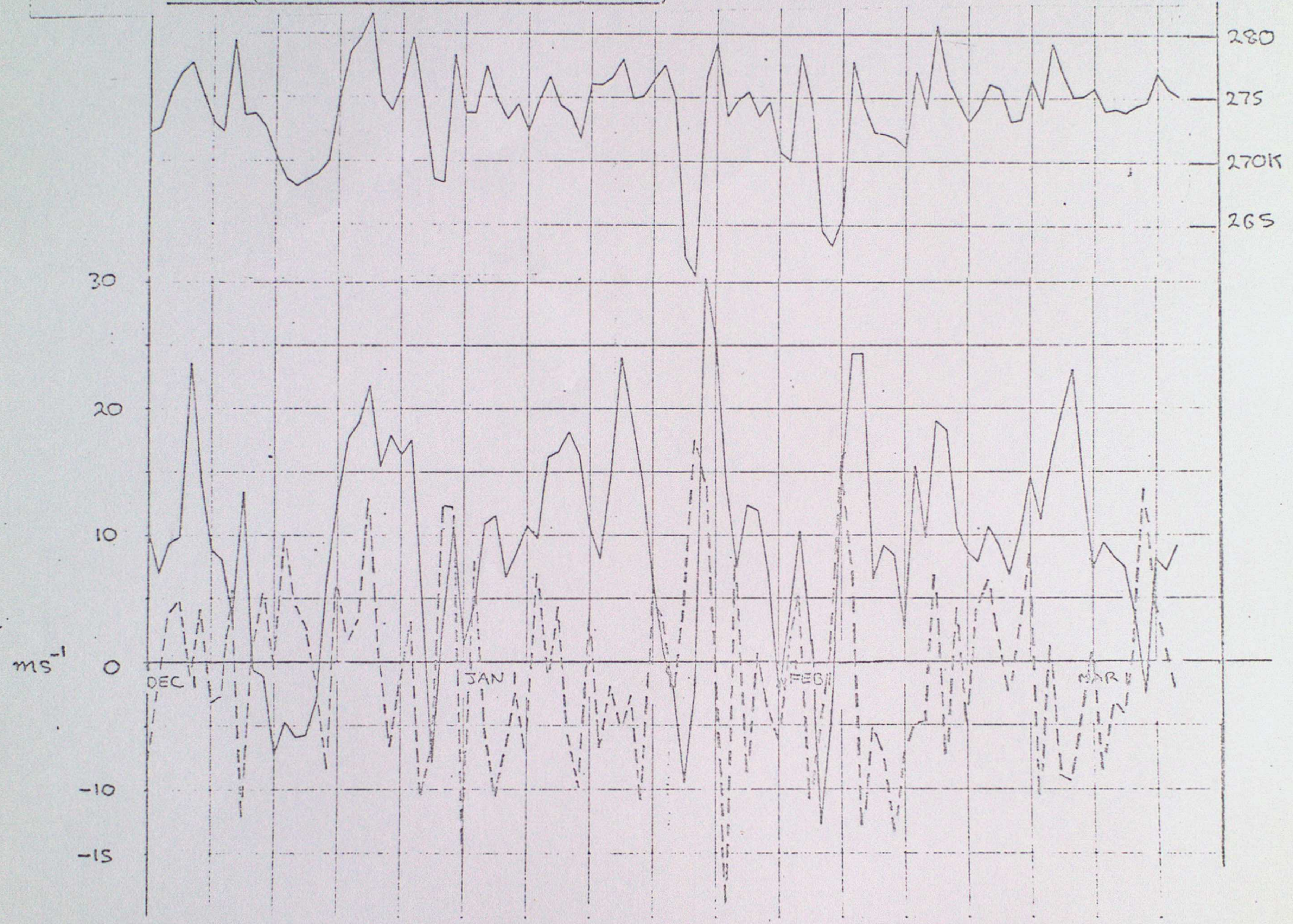
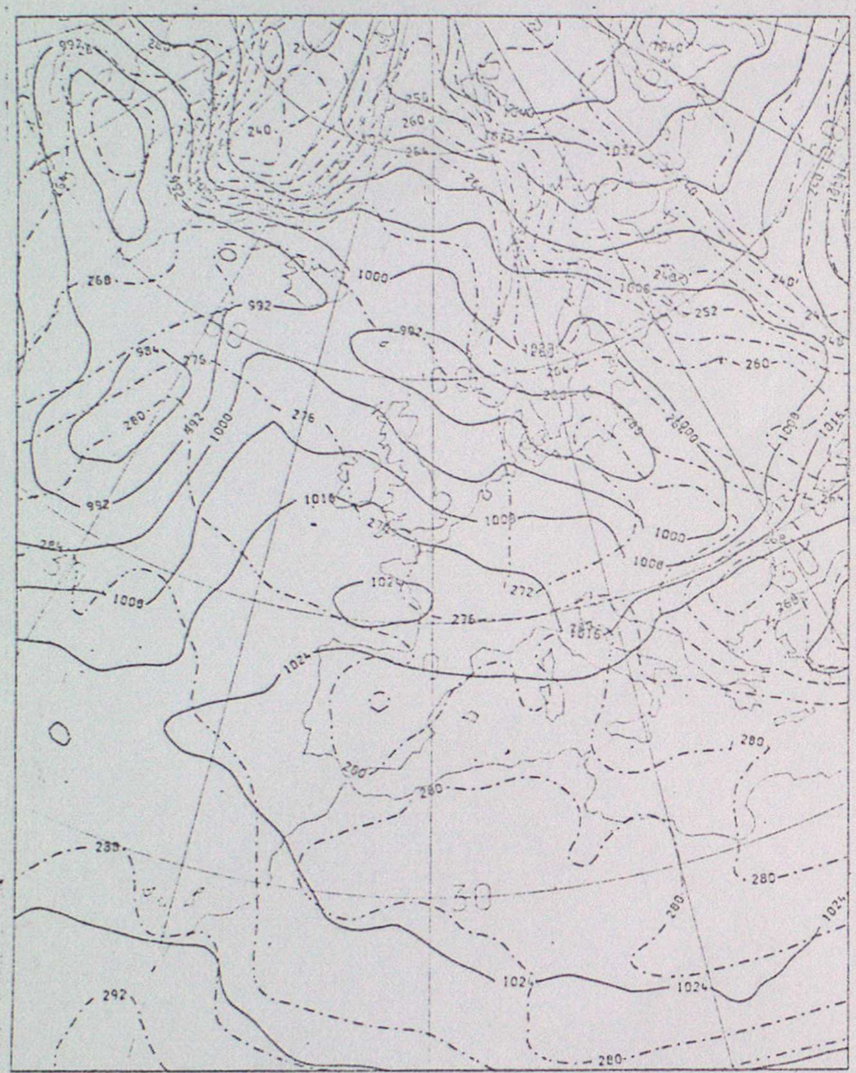
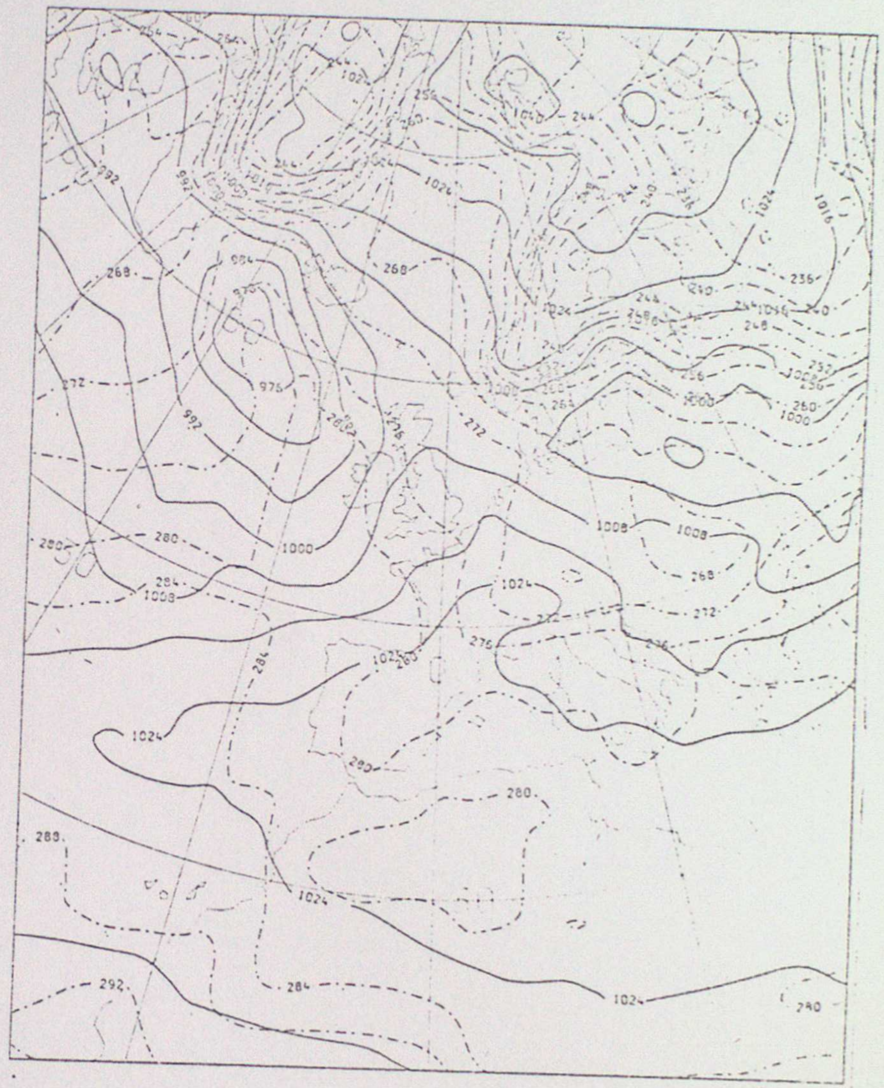


Figure 5

Mean sea level pressure (mb) and temperature at $\sigma = .9$ (K)



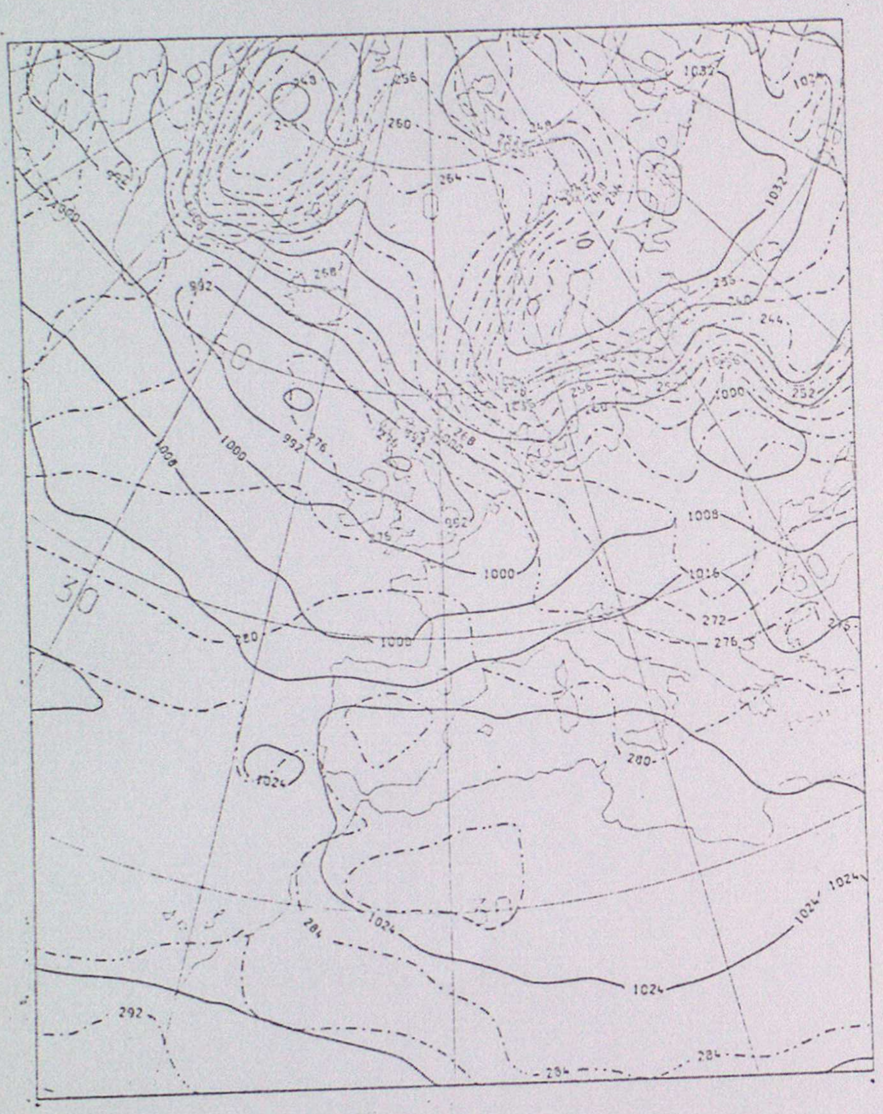
(a) Day 640



(b) Day 641

Figure 5

Mean sea level pressure (mb) and temperature at $\sigma = .9$ (K)

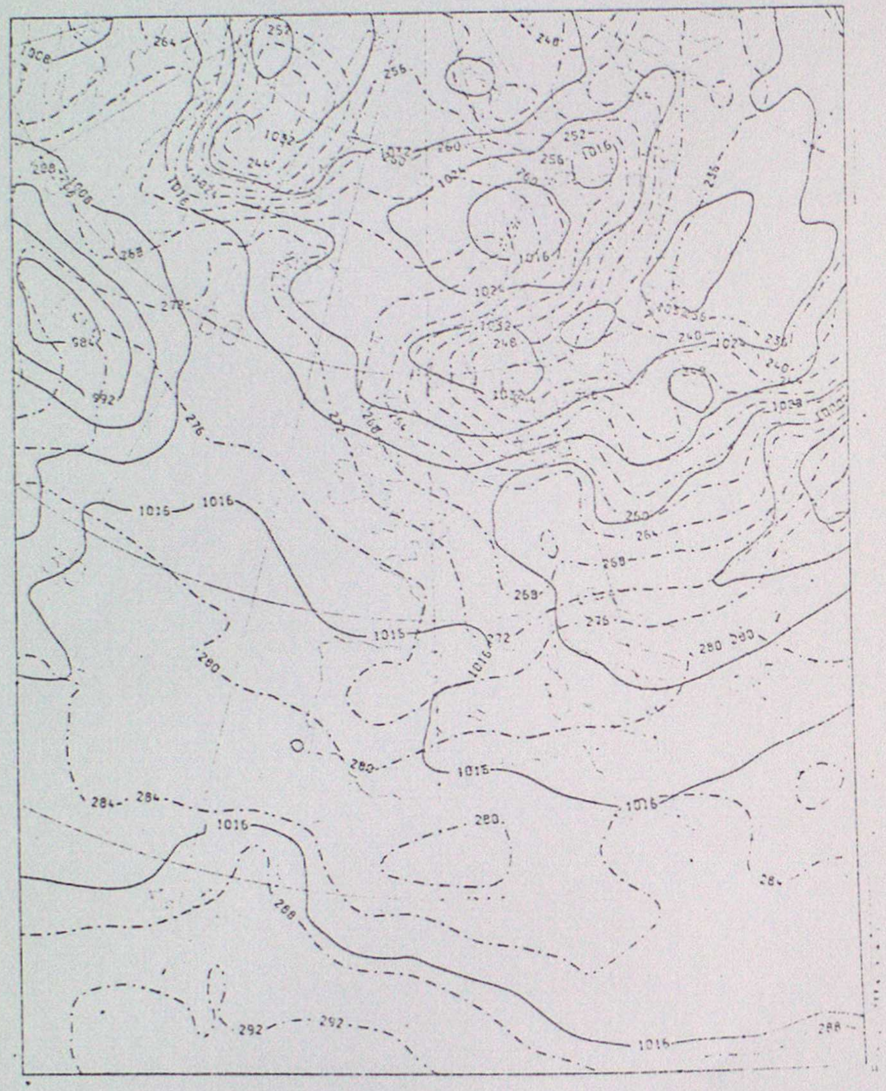


(c) Day 642

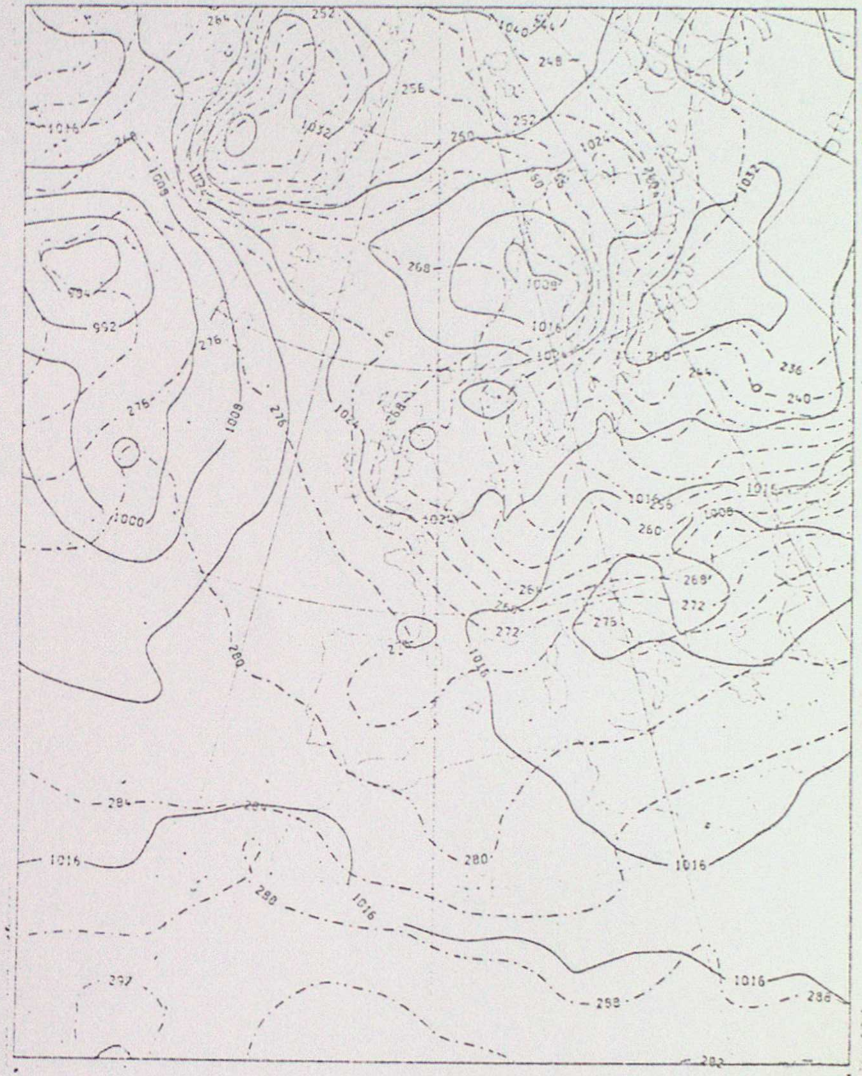
(d) Day 643

Figure 5

Mean sea level pressure (mb) and temperature at $\sigma = .9$ (K)



(e) Day 644

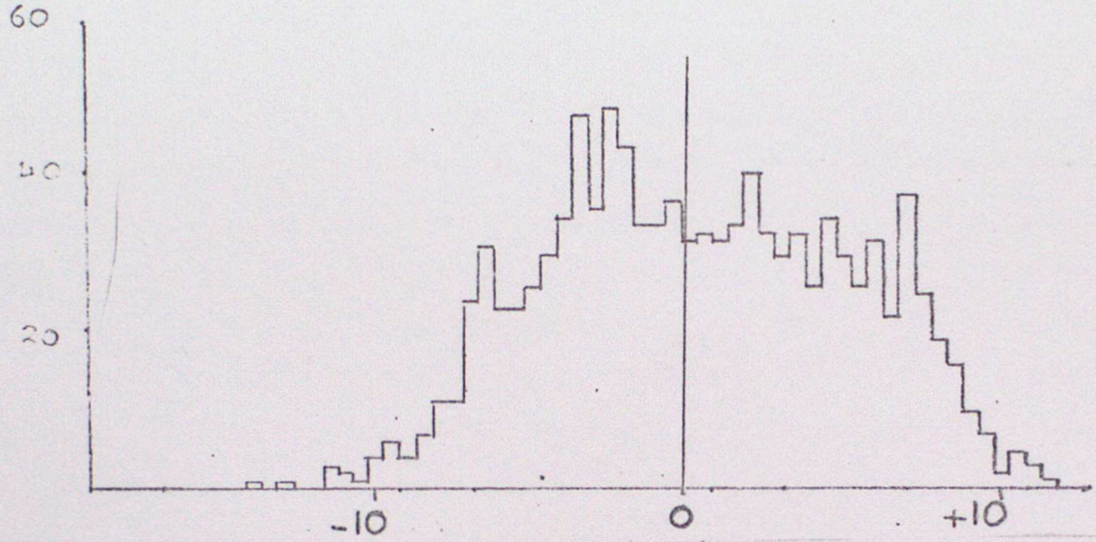


(f) Day 645

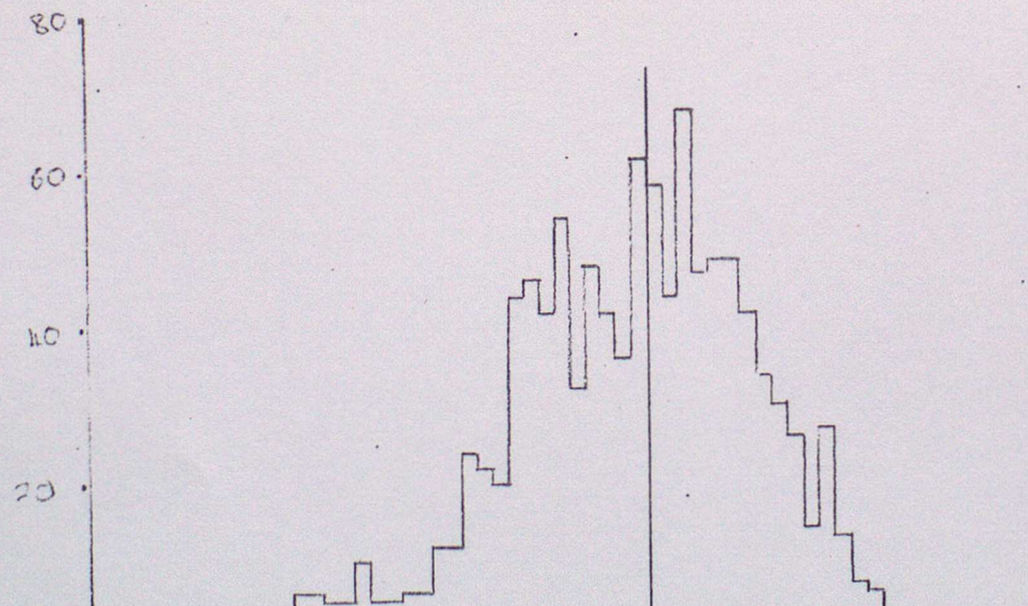
Figure 6

Histograms of temperature with the mean removed.

Horizontal axis: K
Vertical axis: No. of events per .5K



1100 days Central England temperatures starting 1st January 1971

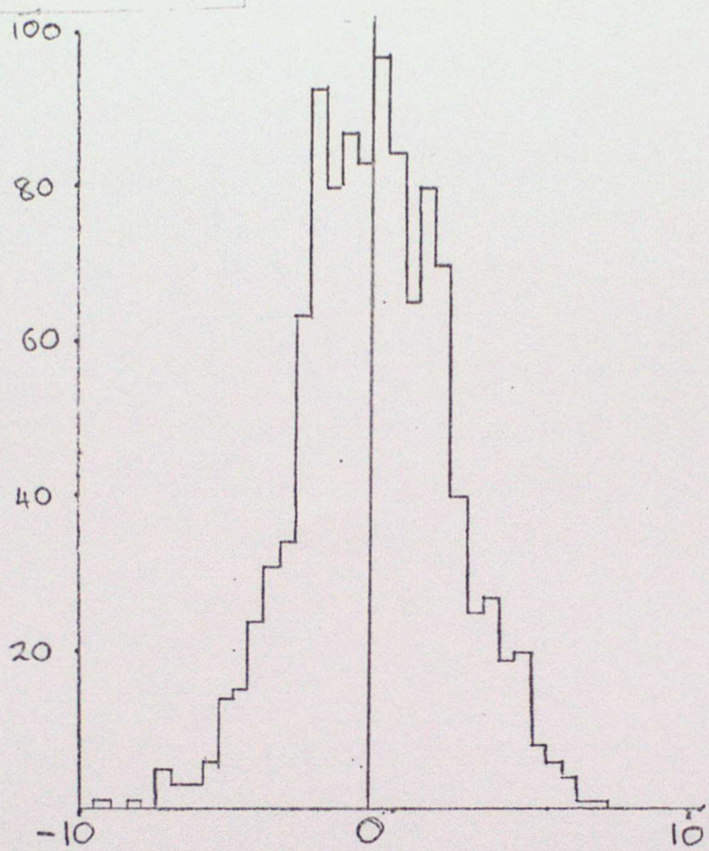


1090 days model temperatures at $\sigma = .9$ for the eastern England grid box

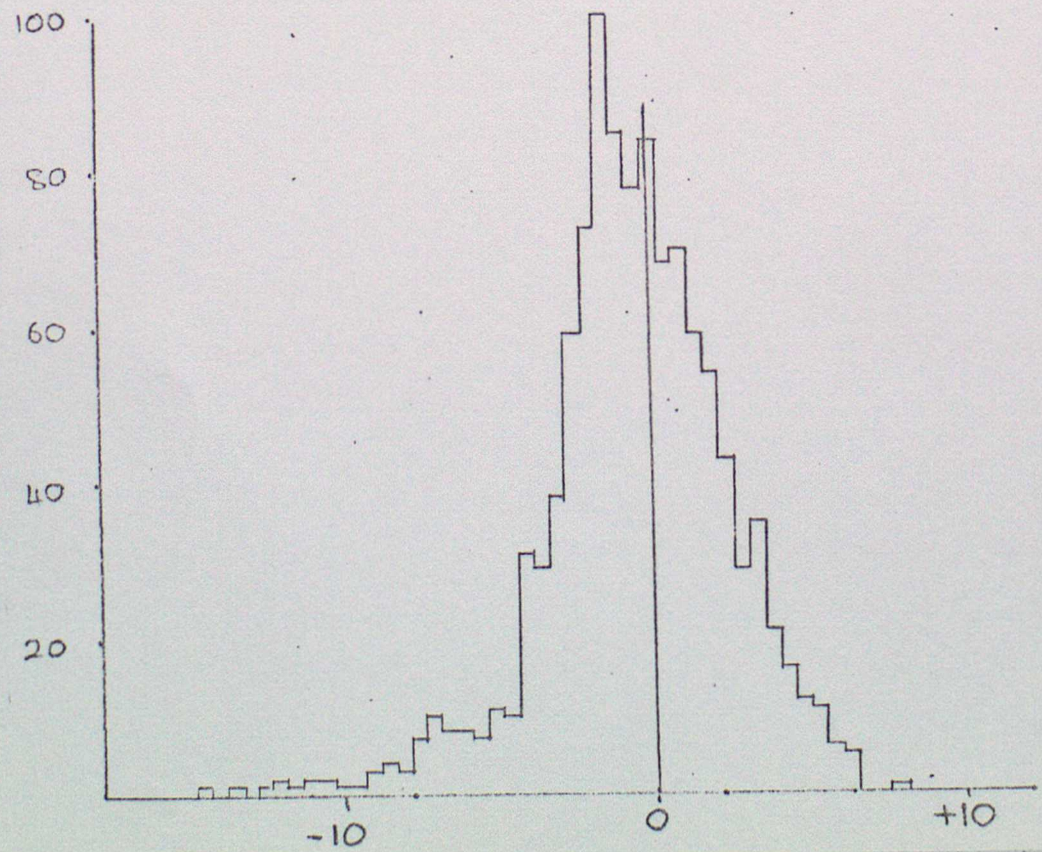
Figure 7

Histograms of temperature with the mean, annual and semi-annual cycles removed.

Horizontal axis: K
Vertical axis: No. of events per .5K



1100 days Central England temperatures starting 1st January 1971



1090 days model temperatures at $\sigma = .9$ for the eastern England grid box

Figure 8

Theoretical $\log_{10}$ power spectral density for a first order autoregressive process

$\tilde{z}_t = \phi_1 \tilde{z}_{t-1} + a_t$ where $\sigma_a = 1$ and $\phi_1 = .8$

Vertical axis : $p(f)$ where $p(f) = \dfrac{2\sigma_a^2}{|1 - \phi_1 e^{-i2\pi f}|}$ $0 \leq f \leq \frac{1}{2}$

Horizontal axis : $2\Delta t f$

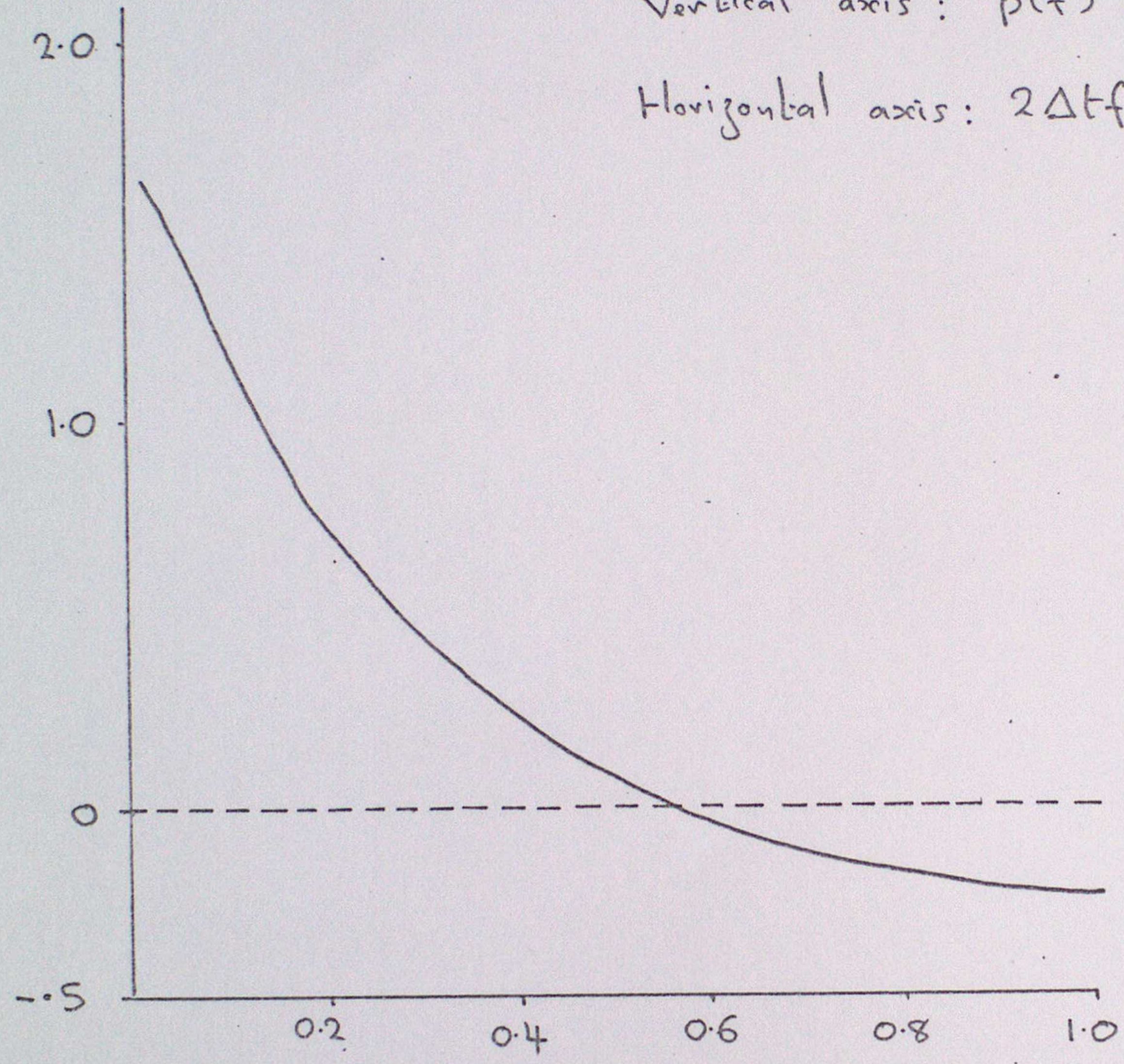
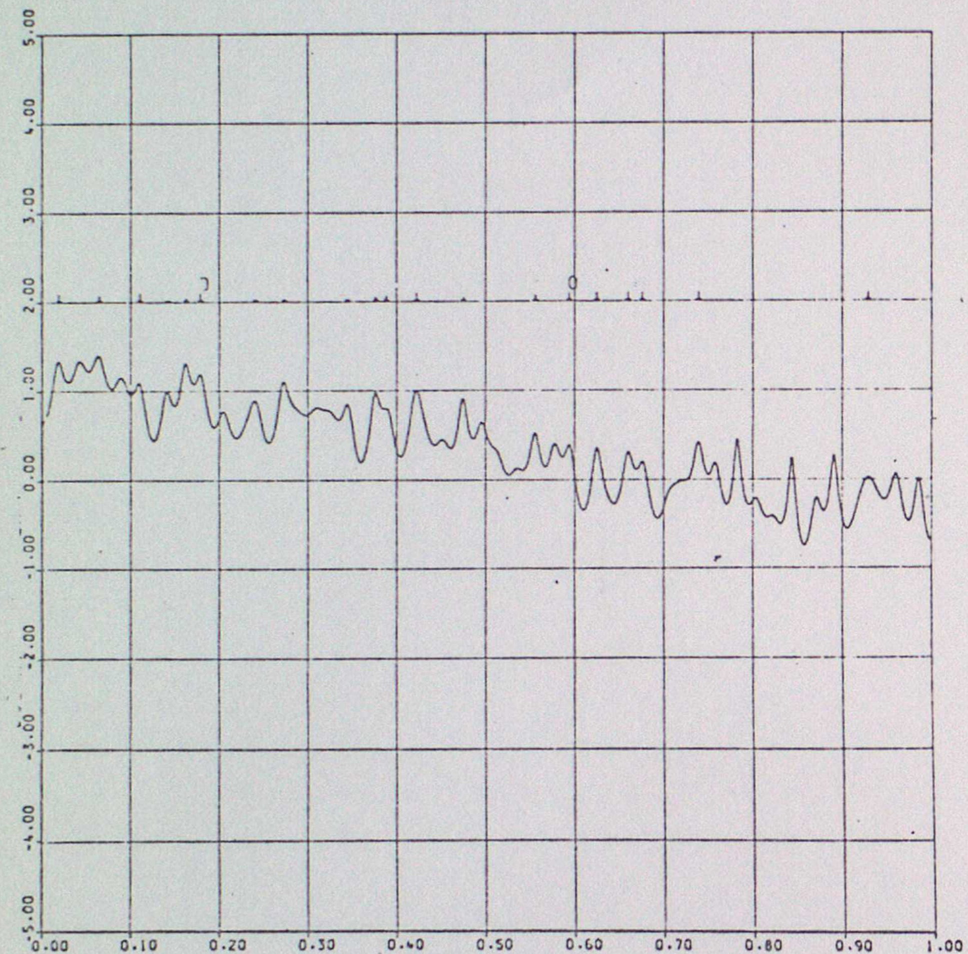


Figure 9

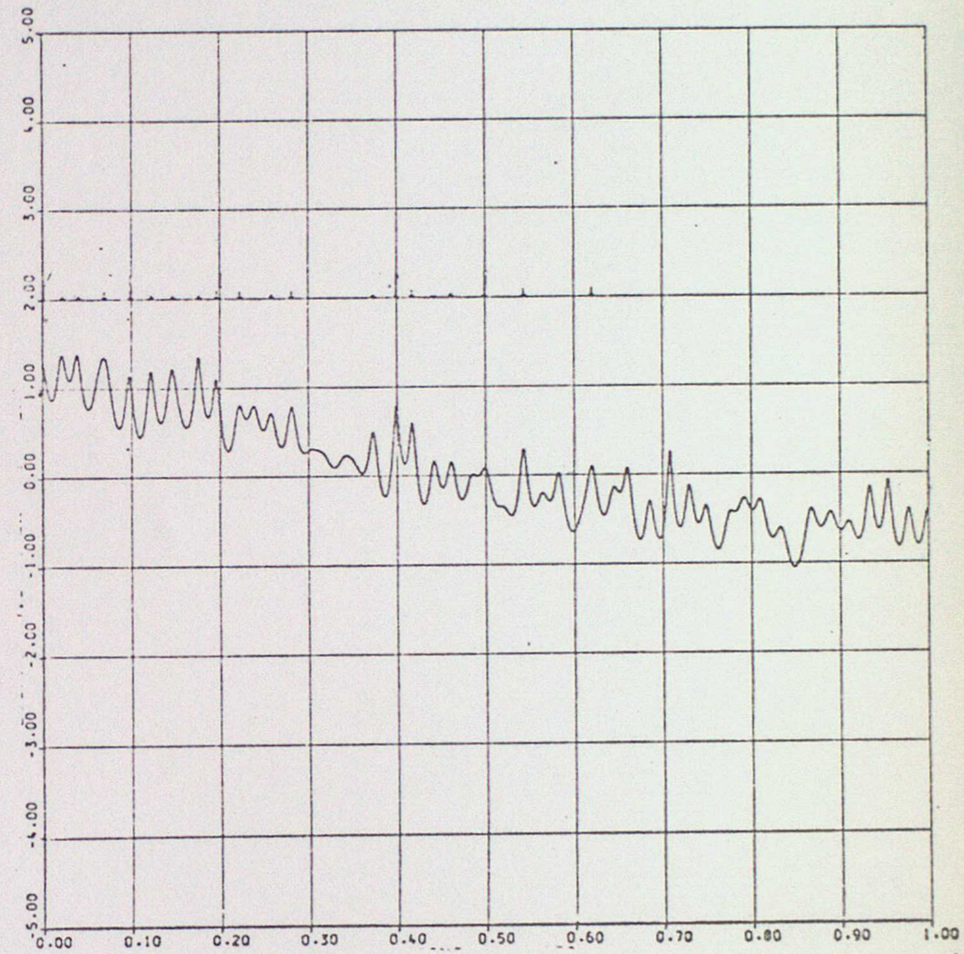
$\log_{10}$ Power Spectral Density $\left(S(f) = \Delta t \sum_{k=-\infty}^{\infty} \phi(k) \exp(-2\pi i f k \Delta t) \text{ where } \phi(k) = E[x_j x_{j+k}] \right)$

estimated by a maximum entropy method , vertical axis = $\log_{10}(S(f))$, horizontal axis = $2\Delta t f$



1090 days model temperatures at σ = .9 for the

eastern England grid box

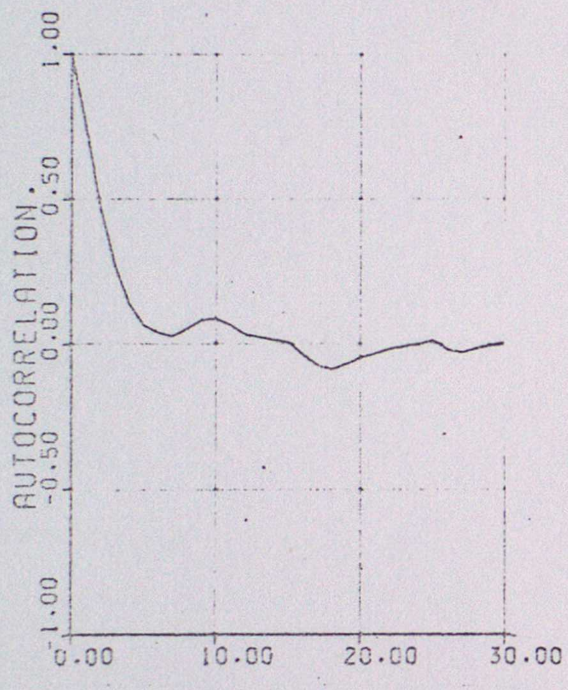


1100 days Central England Temperatures

starting 1st January 1971

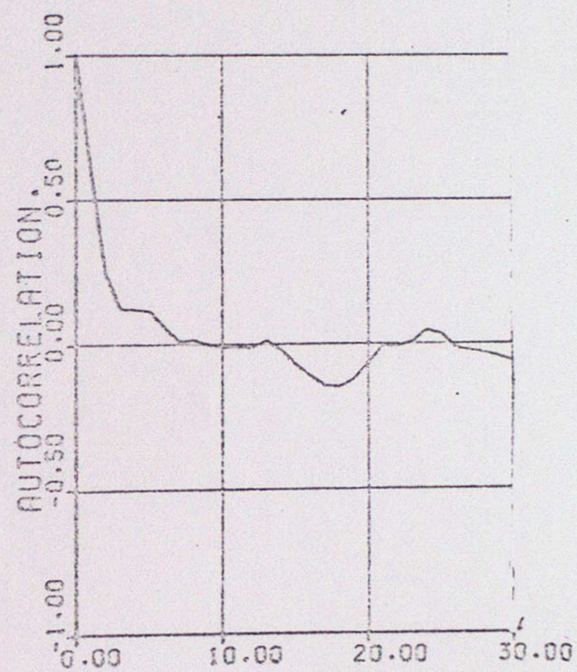
Figure 10

Autocorrelograms (data with trend, mean, annual and semi-annual cycles removed)



1090 days model temperatures at $\sigma = .9$

for the eastern England grid box



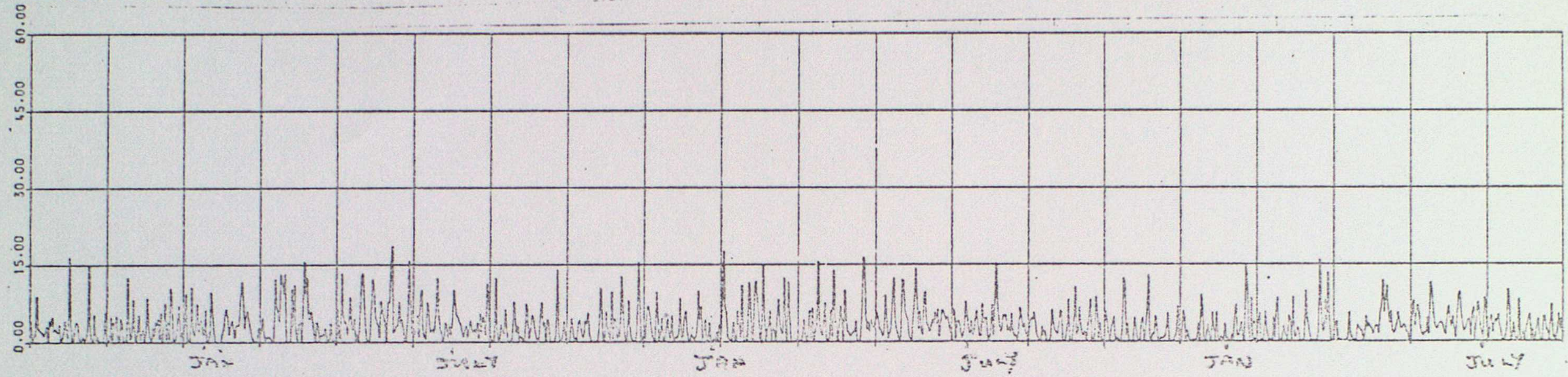
1100 days Central England Temperatures

starting 1st January 1971

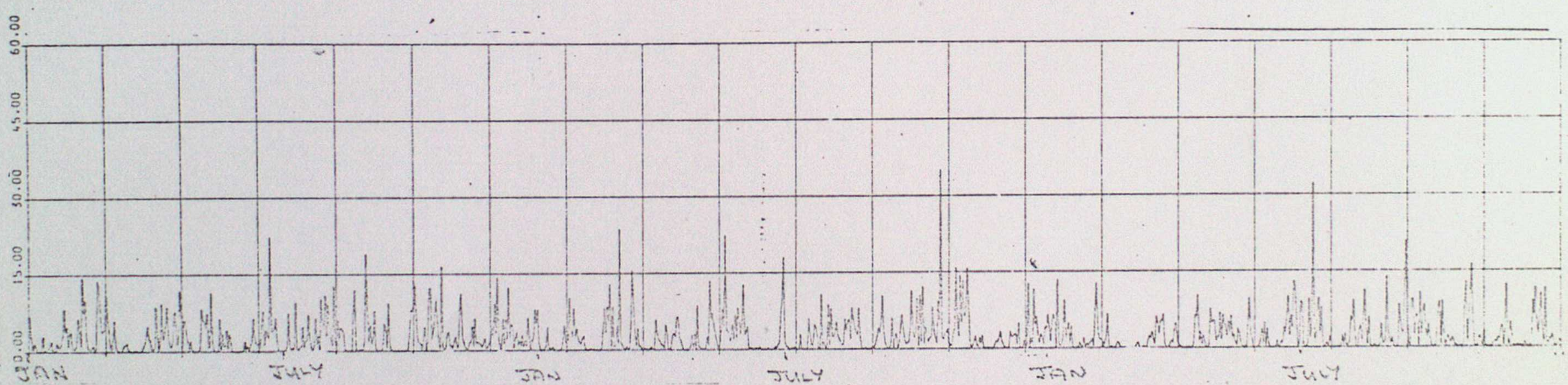
Figure 11

Time series

Vertical axis: mm



(a) 1100 days model precipitation for the eastern England grid box.

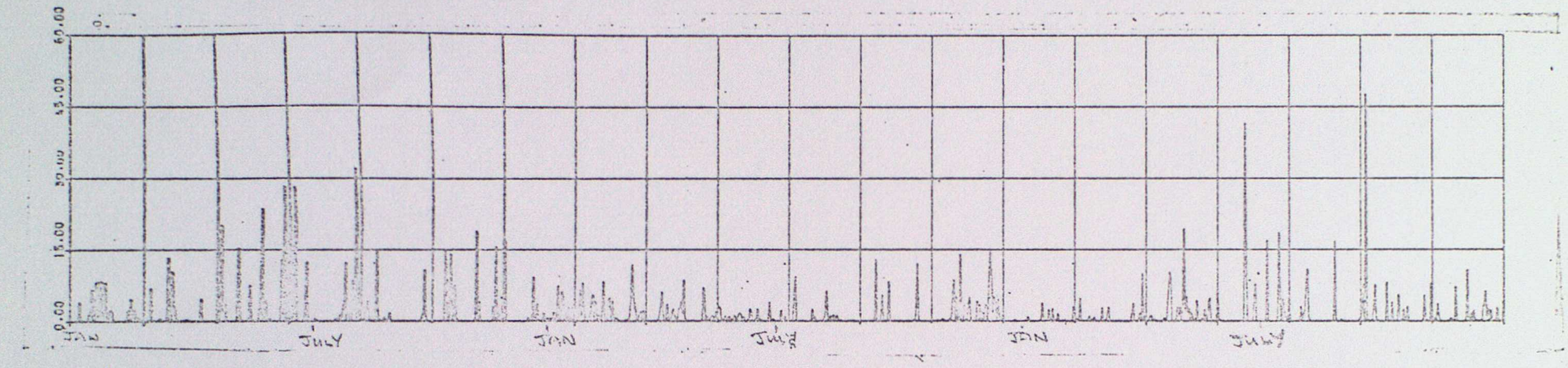


(d) 1100 days rainfall for the England and Wales rainfall starting 1st January 1971

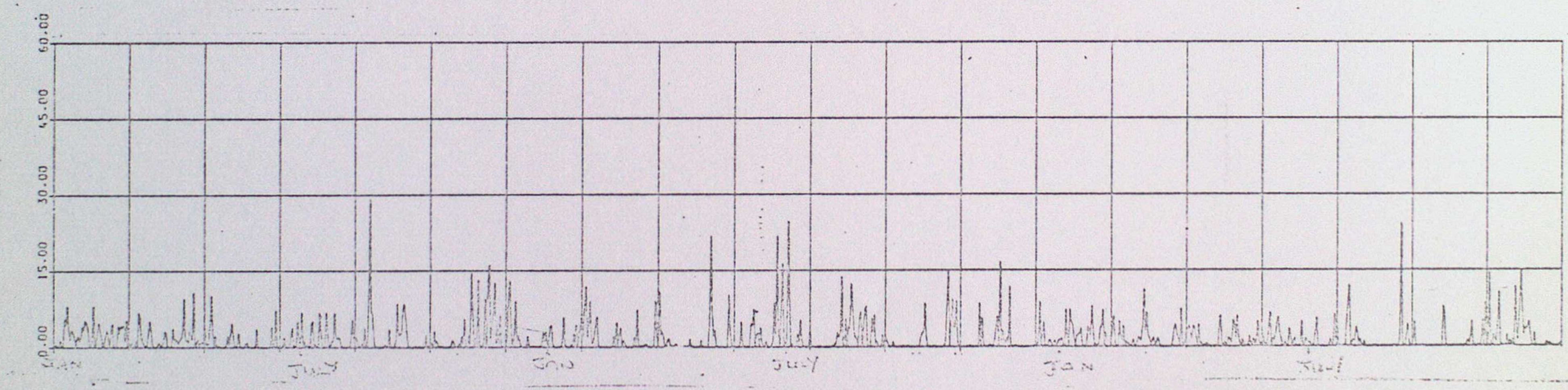
Figure 11

Time series

Vertical axis: mm



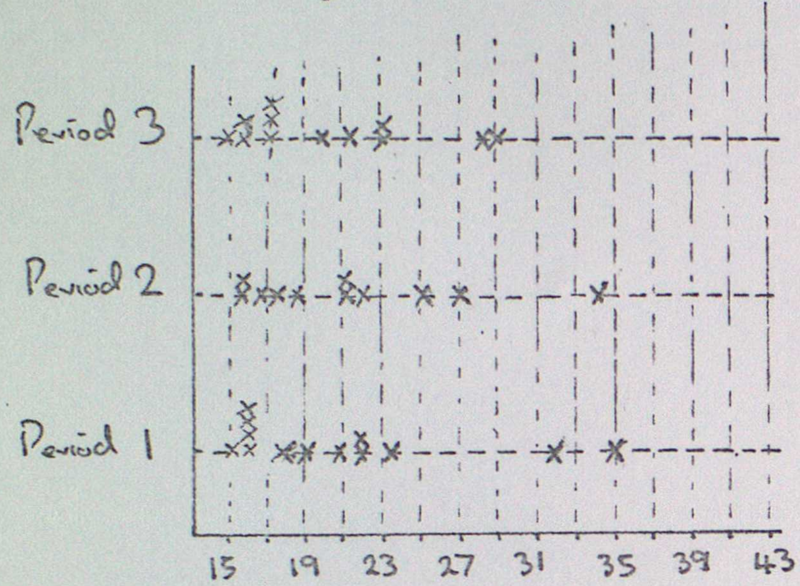
(b) 1100 days rainfall for Kew starting 1st January 1971



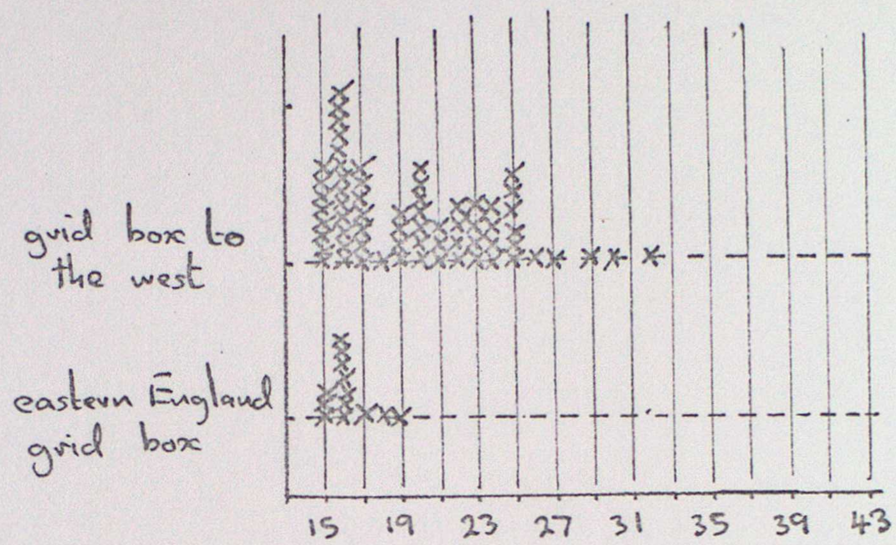
(c) 1100 days rainfall for the long period stations starting 1st January 1970

Figure 12 Number of Days with precipitation above 15mm

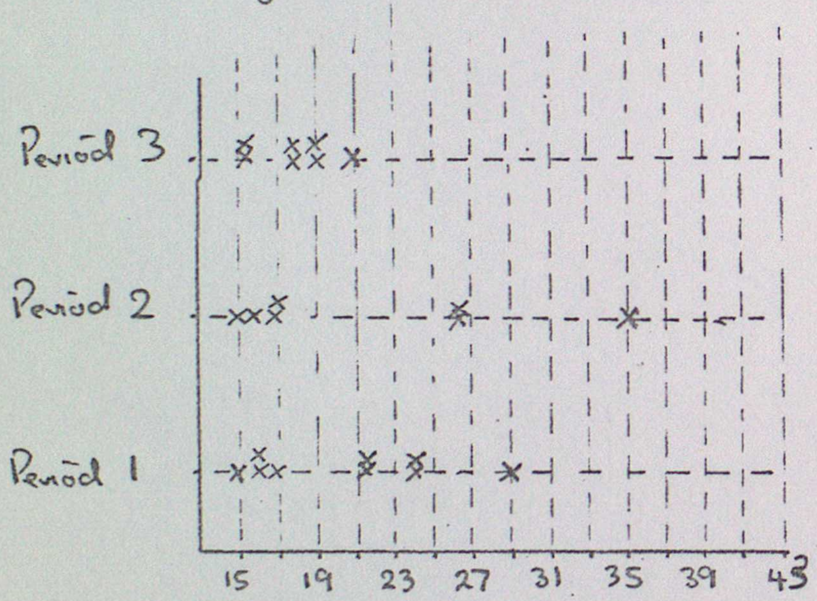
Horizontal axis : mm , Vertical axis : Number of days



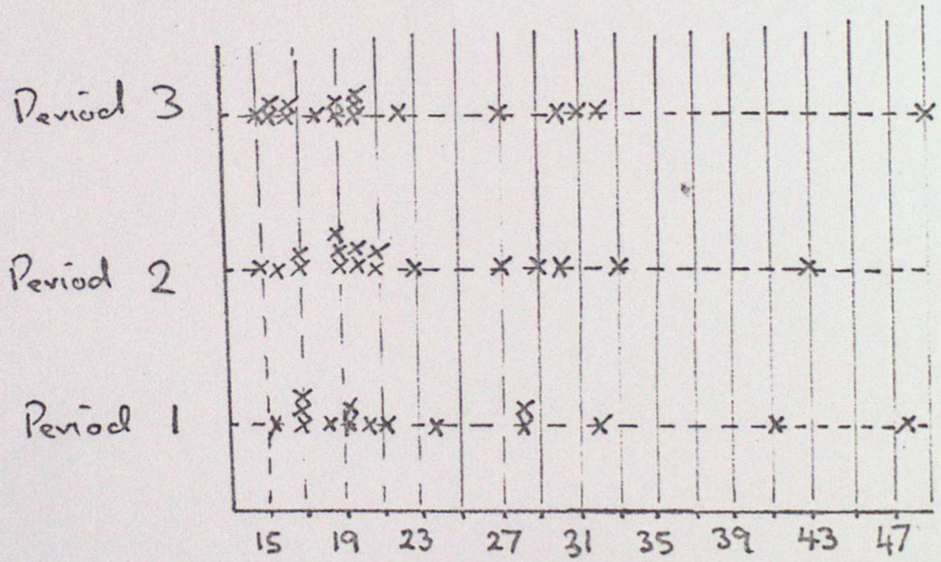
England and Wales



Eastern England grid box and the grid box to the west.



Long Period Stations

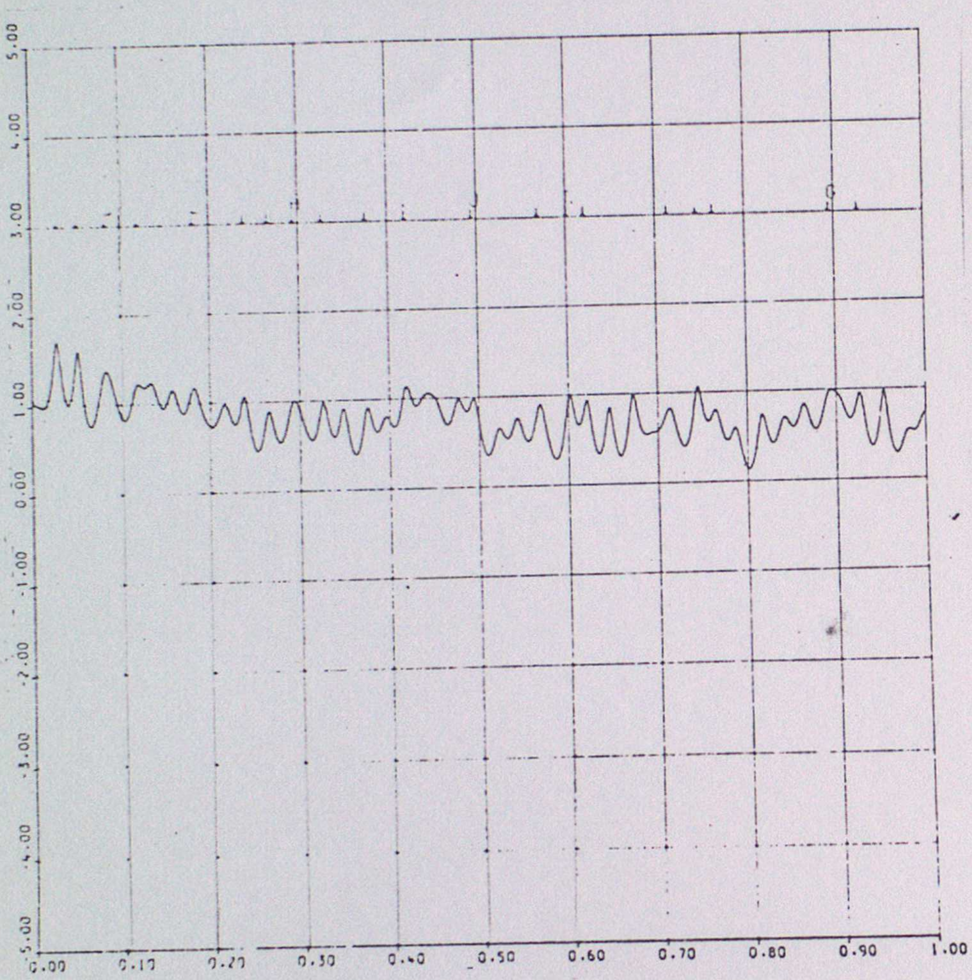


Kew

Figure 13

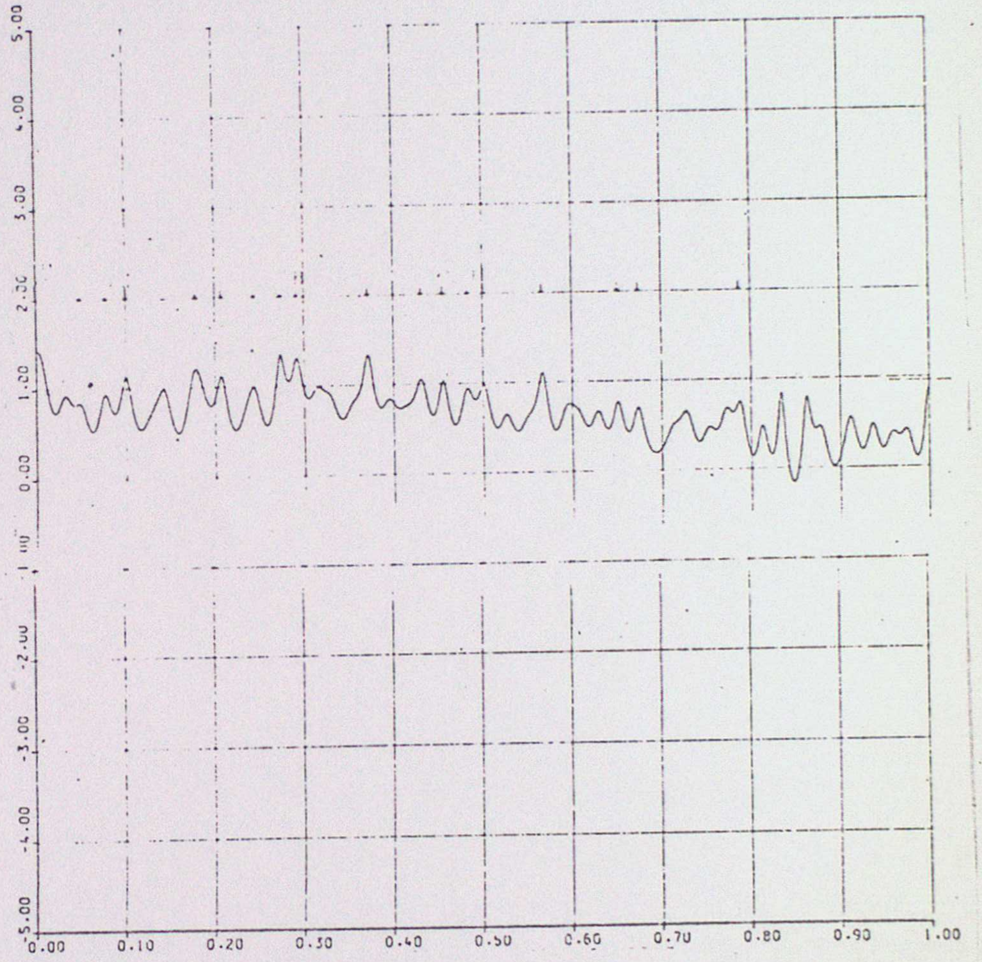
$\log_{10}$ Power Spectral Density $\left(S(f) = \Delta t \sum_{k=-\infty}^{\infty} \phi(k) \exp(-2\pi i f k \Delta t) \text{ where } \phi(k) = E[x_j x_{j+k}] \right)$

estimated by a maximum entropy method, vertical axis = $\log_{10}(S(f))$, horizontal axis = $2\Delta t f$



1100 days rainfall for the England and Wales rainfall

starting 1st January 1971

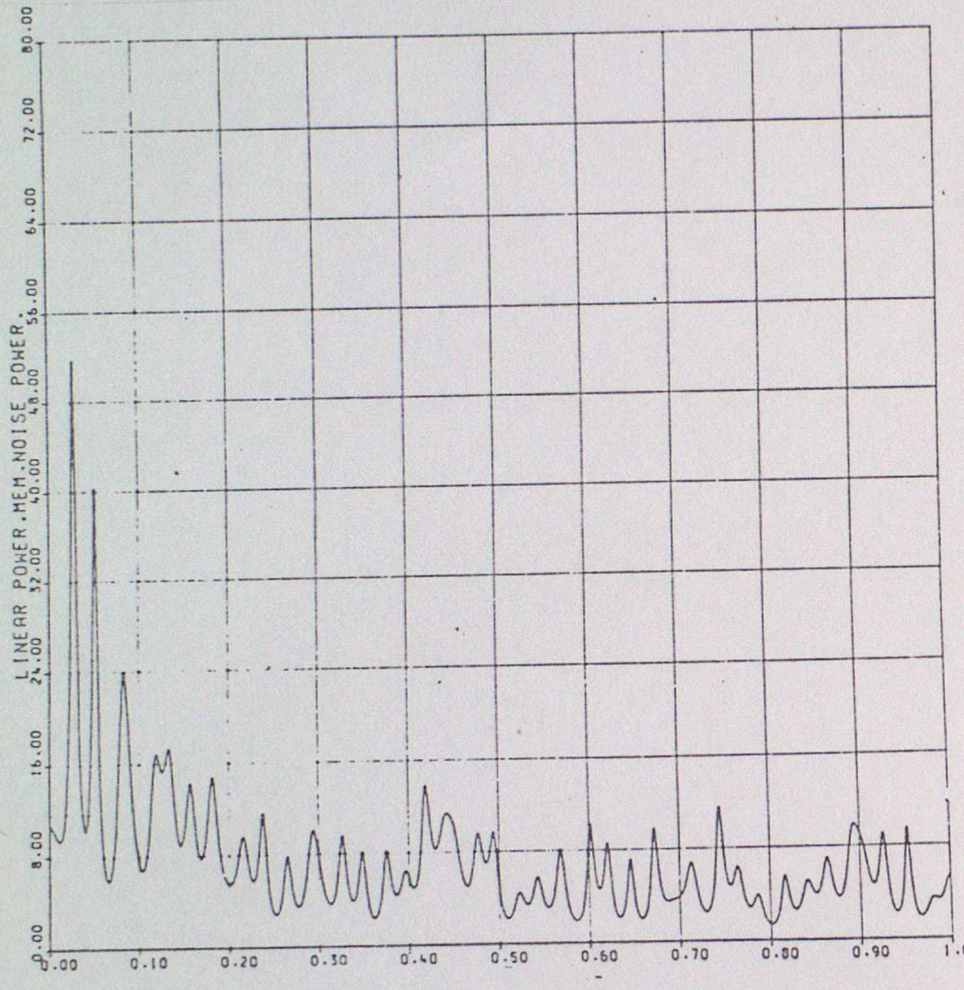


1100 days model precipitation for the eastern England grid box

Figure 14

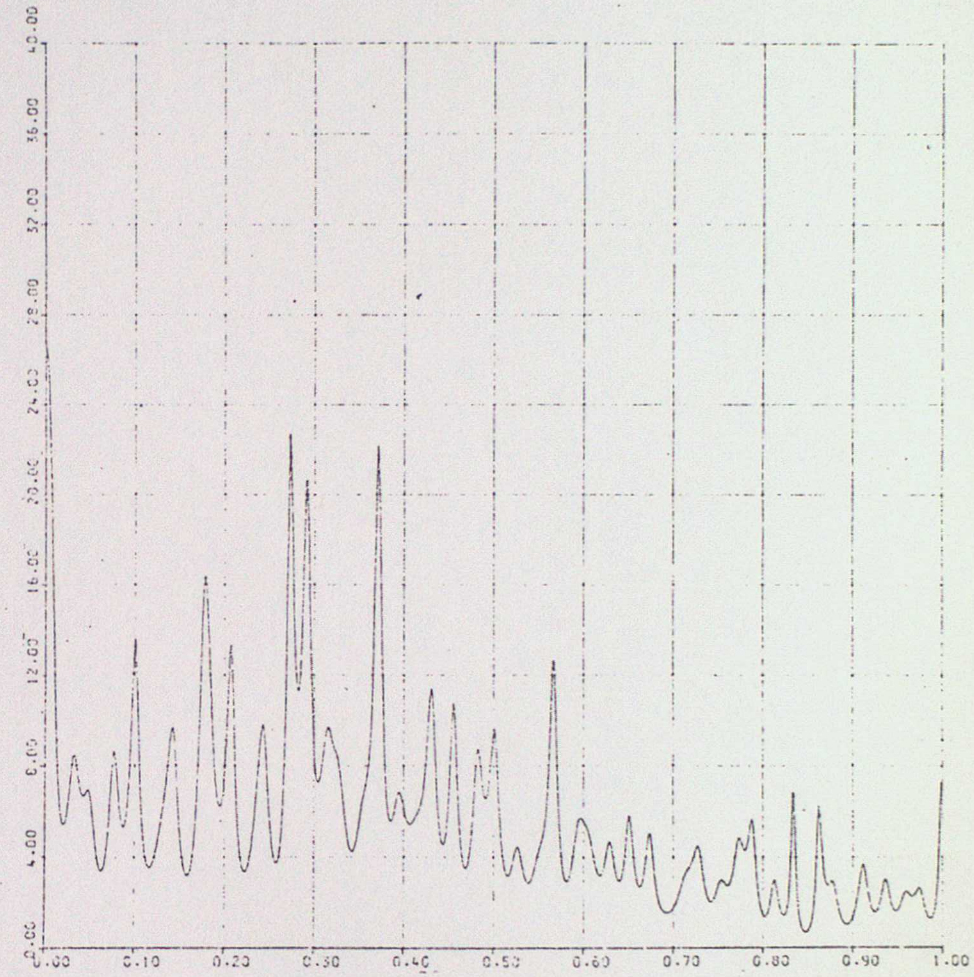
Power Spectral Density $\left(S(f) = \Delta t \sum_{k=-\infty}^{\infty} \phi(k) \exp(-2\pi i f k \Delta t) \text{ where } \phi(k) = E[x_j x_{j+k}] \right)$

estimated by a maximum entropy method, vertical axis = $S(f)$, horizontal axis = $2\Delta t f$



1100 days rainfall for the England and Wales rainfall

starting 1st January 1971

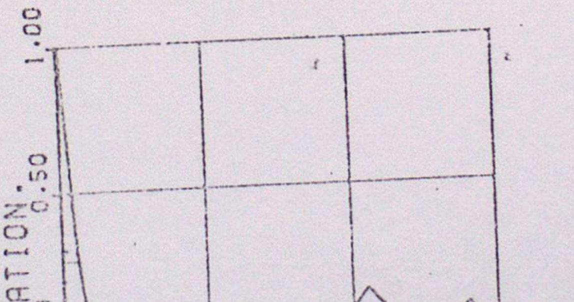


1100 days model precipitation for the eastern England grid box

Figure 15

Autocorrelograms (data with trend and mean removed)

1100 days rainfall for the England and Wales rainfall starting 1st January 1971



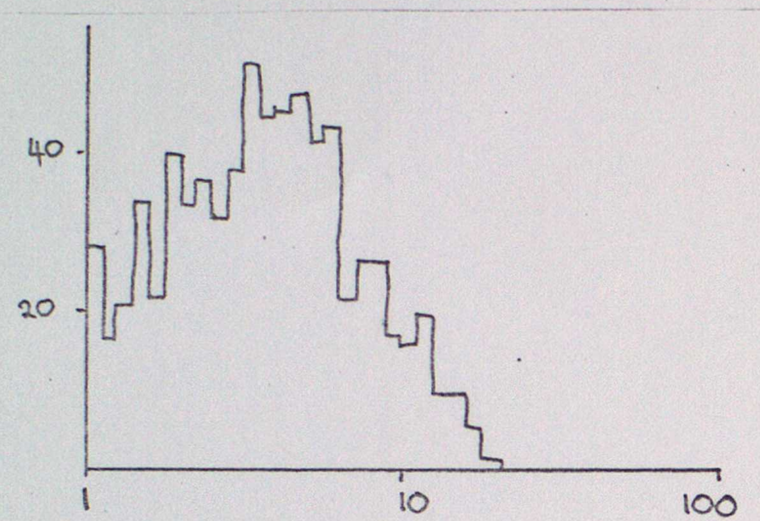
1100 days model precipitation for the eastern England grid box

Figure 16

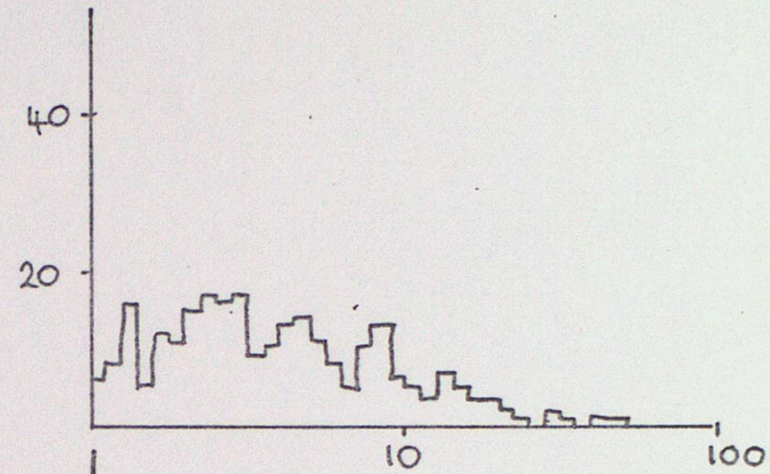
Histograms of the log. of precipitation

Horizontal axis: mm

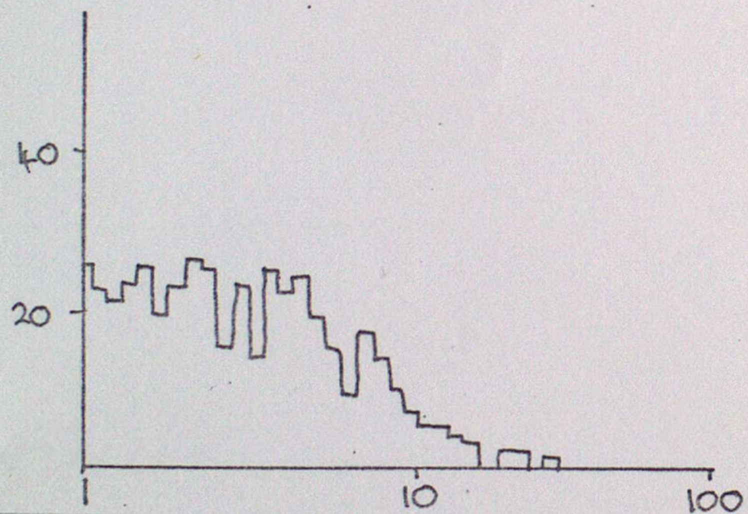
Vertical axis: number of events per .05 log(mm)



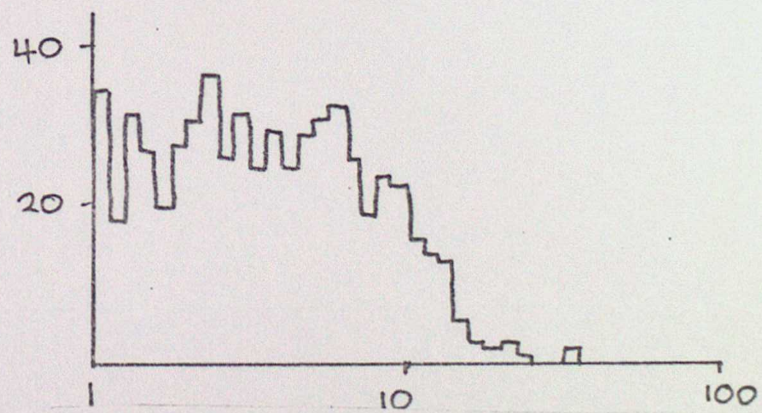
1100 days model precipitation for the eastern England grid box



1100 days rainfall for Kew starting 1st January 1971



1100 days rainfall for the long period stations starting 1st January 1970



1100 days rainfall for the England and Wales rainfall starting 1st January 1971