Tellus (1983), *35A*, 389–397

The yearly averaged air temperature in Rome from 1782 to 1975

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(Manuscript received August 12; in final form December 3, 1982)

ABSTRACT

Air temperature data of Rome are analysed to point out the variations caused by natural events and human activities. In particular, the influence of the growth of the city on the minimum average temperature is evident. It is also found that the air temperature seems to be affected by the solar cycle.

1. Introduction

There is a growing interest in studies on climate and its variations for the purpose of developing models for forecasting the climatic evolution of the planet and to discover any modifications introduced in it by human activities. The analysis of long series of meteorological data provides important information, of use in attaining these two interrelated objectives. Much work has been done on air temperatures, since variations in this parameter are considered more indicative of any climatic variations.

A first type of analysis deals with the study of temperature variations as a function of time, both in an attempt to find patterns and, when the data refer to the urban environment, to discover alterations induced in the temperature itself through human activity (urban heat island). A wide-ranging survey of the subject is contained in Oke (1974, 1979), Garstang et al. (1975) and Landsberg (1981), who examine the structures of the heat island as a function of the size and growth rate of the city. The link between air temperature and the solar cycle has been studied extensively. Currie (1974, 1979, 1981) has analysed long time series of temperature data referring to North American cities. He detected a 10.6 year cycle associated with the solar cycle. The connection between temperature and solar activity is confirmed by Hoyt (1979), Schönwiese (1981) and Bücher (1981).

Mass and Schneider (1977) on the other hand are somewhat sceptical: in their analysis, in fact, they concluded that a connection between temperature and solar activity is unlikely.

In the present work, the mean yearly temperature data in Rome are analysed for the purpose of: (i) reconstructing the history of this meteorological parameter, identifying trends and comparing the latter with those of other European and Italian cities; (ii) evaluating the effect of the city's growth on temperature trends and (iii) by applying spectral analysis techniques, finding characteristic frequencies to be correlated with astronomical influences, if any. In particular, after a short description of the data set used, an analysis of the raw data is given to show that the minimum temperature trends differ from the medium and maximum ones. The trend analysis carried out using low-pass numerical filters confirms this characteristic which, by comparison with other data, is found to be shared by other cities. An analysis is then made of the urban island heat effect, and the application of simple correlation models provides a satisfactory explanation of the minimum temperature trend. Lastly, spectral analysis reveals a peak at around 11 years which can probably be attributed to the solar cycle effect.

as will be shown by the analysis of correlation with the sunspot number series.

2. Data set

The data analysed are typical of the Rome urban situation since they were recorded at the "Collegio Romano" station in the city centre. The meteorological station is situated at 58.5 m above mean sea level and 41 m above the level of the city.

Measurements began in 1782 using a Reamur thermometer, and from 1826, maximum and minimum temperature measurements were also made using a Bellani thermograph. In 1843, owing to the errors introduced by this instrument, a systematic comparison with data from normal thermometers was begun and a control carried out on the data previously collected. As a result, minimum and maximum temperatures can be considered reliable only from 1831 on. The data collected were recorded in registers. Copies are available for the period 1782–1792. For the period 1793–1810, both the registers and the copies are missing. The data are again available from 1811. The data are subsequently always available, except for the year 1824, for which both registers and copies have been lost. Three or four recordings were generally made every day. However, the analyses reported in the present paper refer to yearly averaged data. For the period 1782–1910 the yearly averaged values were tabulated by Eredia (1911), while for 1911–1978 they were copied from the register currently in the possession of the "Ufficio Centrale di Ecologia Agraria" of the Ministry of Agriculture.

3. Data analysis

3.1. *Raw data analysis*

Fig. 1 shows yearly averaged values of air temperature in Rome. T_{mean} is the yearly average temperature obtained from the mean daily temperatures; the yearly averaged minimum and maximum temperatures are T_{min} and T_{max}, respectively. From Section 2 it is clear that recordings do not start in the same year as the extreme temperatures. They start in 1831. The mean temperature for the whole record is 15.5 °C. During the period 1811–1905 the yearly averages fluctuate around this value. After that, they tend to increase and the temperature remains above the mean value. A tendency to decreasing temperature is found from 1961. In Fig. 2b, the mean temperature distribution is given over the range 13.5°–17.5 °C, divided into 0.5 °C steps. This histogram shows that 74% of the values lie in the range between 14.5 °C and 16.5 °C. The values at the extreme end of the range are very low; the mean temperature only occurs twice in the 13.5°–14.5 °C step, and only twice in the higher 17°–17.5 °C step. The distribution of the yearly average maximum temperatures shows a similar trend to that of the mean temperatures. The mean value for the whole record is 20.4 °C. In the period 1831–1846, the values are above the average. In subsequent years, up to 1920, the values are around or slightly less than the average. In the period 1921–1964, the temperatures are higher than the record average and show a decrease in recent years. Fig. 2c shows the distribution of maximum temperatures; the histogram shows that the majority of values (81%) lie between 19.5 °C and 21 °C. The minimum

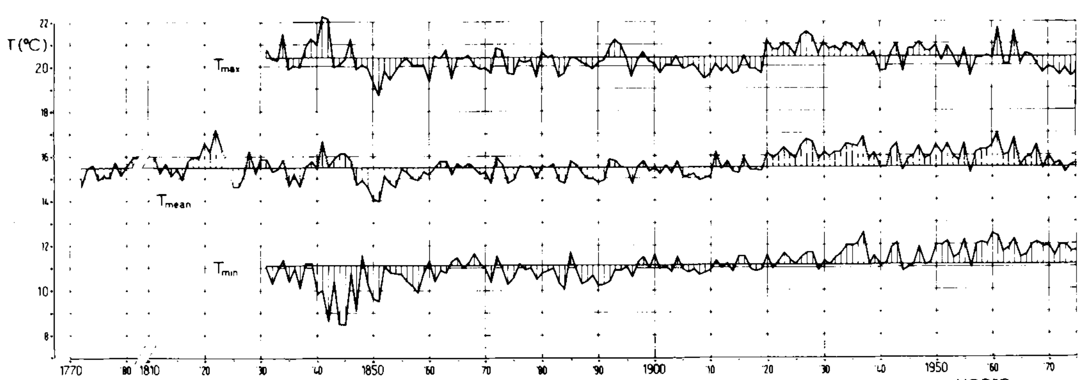

Fig. 1. Yearly averaged values of air temperature in Rome.

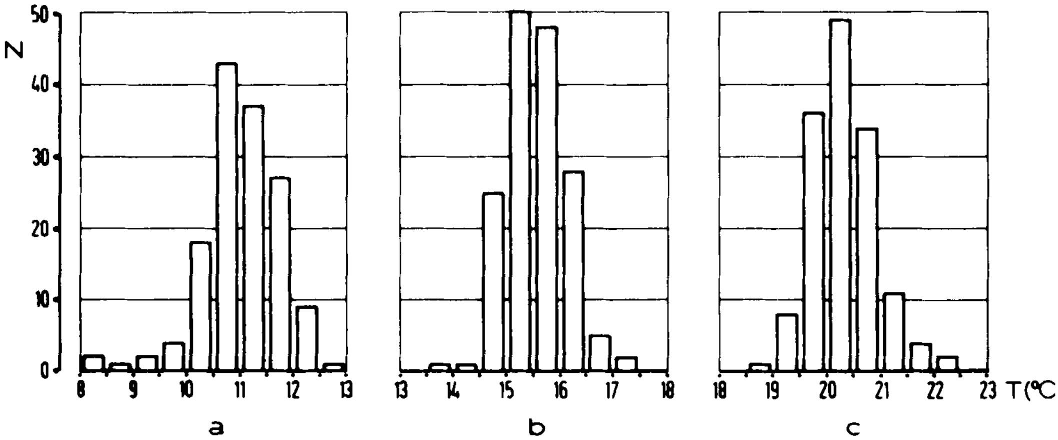

Fig. 2. Histogram distribution of the air temperatures: (a) mean minimum; (b) mean; (c) mean maximum.

temperatures show a different pattern. During the period 1831–1890, the values are lower than the record average of 11.1 °C. Between 1890 and 1930 there are slight fluctuations around this mean value. After 1930 there is a sharp increase, probably due to the growth of the city. This is confirmed in the distribution of values (Fig. 2a) in which the histogram shows that maximum data concentration (75%) occurs in the 10.5°–12 °C range. The population of the steps in the extreme ends of the range is very low and it is significant that temperatures of less than 9.5 °C are found only during the period 1831–1850.

In order to get an overall idea of the trends, averages were taken for 20-year periods, starting from 1782. The results obtained are shown in Table 1. This first analysis clearly shows that while the mean and maximum temperatures show an increase in the years 1900–1950 and a subsequent slight decrease during recent years, the minimum temperatures show a tendency to increase, also in the period 1951–1970.

Table 1. *20-year averaged air temperatures*

Period	T_{min} (°C)	T_{mean} (°C)	T_{max} (°C)
1782–1794	—	15.4	—
1811–1830	—	15.7	—
1831–1850	10.2	15.4	20.6
1851–1870	10.8	15.2	20.0
1871–1890	10.7	15.3	20.2
1891–1910	11.0	15.3	20.2
1911–1930	11.3	16.0	20.5
1931–1950	11.6	16.1	20.7
1951–1970	11.9	16.0	20.3

3.2. *Trend analysis using low-pass filters*

For a more detailed description of the large time scale behaviour of the Rome air temperature, a numerical low-pass filtering technique was used. By means of this technique, each point in the time sequence is obtained as the weighted mean of the M samples preceding and of the M samples following it. The number M is the filter length and is chosen on the basis of physical criteria (see below). If N is the number of the samples of the yearly averaged temperature (in this case N is the length of the data set), the trend is obtained from the expression

$$\hat{x}_t = \sum_{k=-M}^{M} h_k x_{t-k}, \qquad t = 1, 2, \ldots, N.$$

The filter h_k used in the present analysis is an Ormsby filter (Ormsby, 1961) defined by

$$h_k = \frac{\sin(2\pi f_1 k\,\Delta t)\sin(2\pi f_2 k\,\Delta t)}{2\pi^2 f_2 (k\,\Delta t)^2},$$

with $f_1 = \frac{1}{2}(f_r + f_c)$ and $f_2 = \frac{1}{2}(f_r - f_c)$, where f_r and f_c are known as roll-off frequency and cut-off frequency, respectively. In our case, $\Delta t = 1$ year. The advantage of this type of low-pass filter is that it has unit gain and zero phase shift, i.e. it does not alter signal amplitude in the passing band and does not introduce any shifting in the various harmonics. Filter characteristics may be easily visualized by means of a frequency response curve (Fig. 3b). In order to achieve high filtering

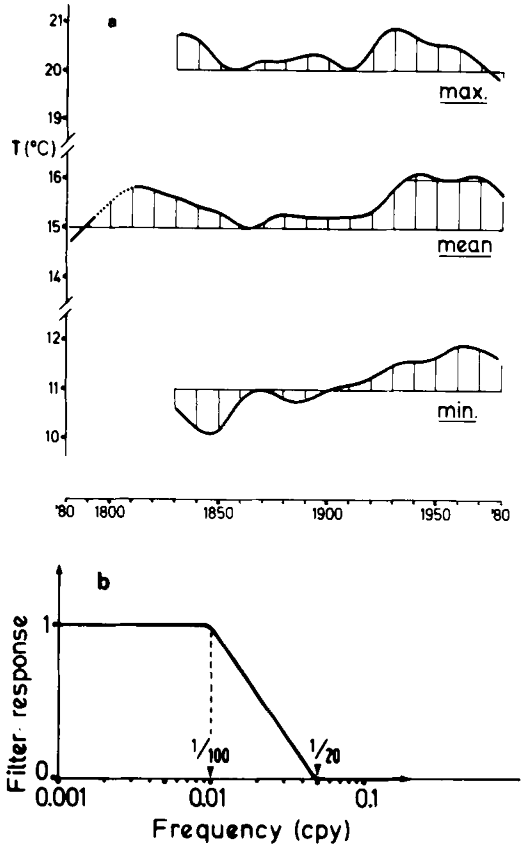

Fig. 3. Trend patterns obtained by numerical filtering applied to Rome temperature data (a), and frequency response of the low-pass filter used in the temperature data processing (b).

accuracy (~1%) it is advisable to select M using the expression

$$M = \frac{2f_N}{f_r - f_c}$$

which, in our case, gives $M \simeq 22$ since, in order to eliminate fluctuations with a period of less than 20 years, $f_r = \frac{1}{20}$ cpy and $f_c = \frac{1}{100}$ cpy were selected. f_N is defined as the Nyquist frequency and is linked to the sampling rate by the expression $f_N = 1/2\,\Delta t$. Lastly, it must be emphasized that the results of this type of analysis are less accurate at the initial and final boundary of the series as the weighted means are effected asymmetrically because of the lack of data left or right of the record. The trends obtained for the three temperature series are shown in Fig. 3a. The mean temperature displays a

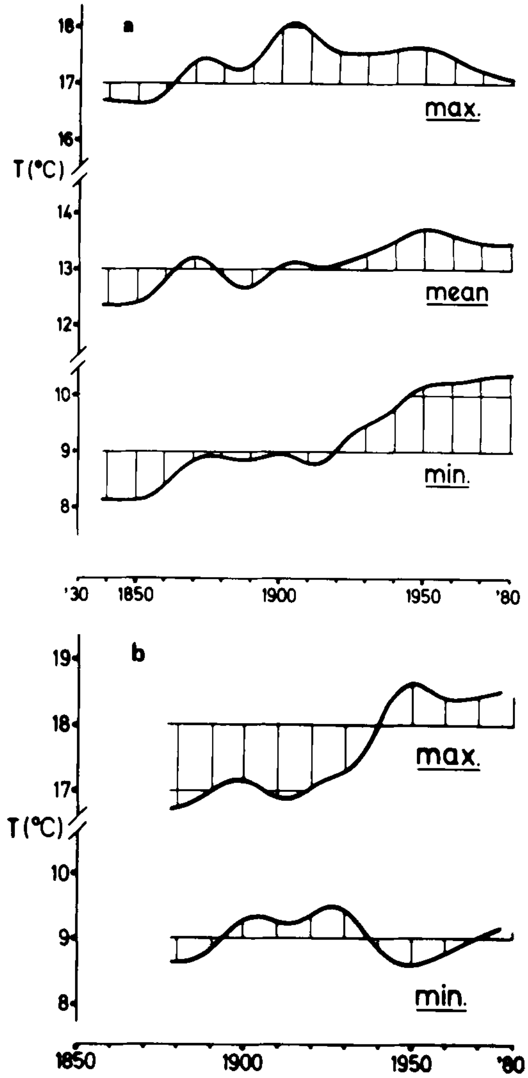

Fig. 4. Trend patterns obtained by numerical filtering applied to Milan (a) and Parma (b) temperature data.

negative trend in the period 1811–1860, with two different gradients: $-0.008\ °C \cdot yr^{-1}$ in the period 1811–1840 and $-0.02\ °C \cdot yr^{-1}$ in the following years. In the period 1855–1970, temperature rises at the rate of $0.03\ °C \cdot yr^{-1}$, and then remains constant for the following 45 years. From 1910 to 1930 there is a further increase, the temperature reaching a value of 16.2 °C, after which it remains constant until 1960. Starting from this year, there is a decrease of $0.05\ °C \cdot yr^{-1}$ which is still in progress. There is a similar trend in the maximum temperatures, which decrease until 1855 and then increase. The maximum temperature remains more or less constant until 1910 and then displays a considerable increase from 1911 until 1930. This is followed by an overall decrease from 1930 to 1975.

The minimum temperatures display a different behaviour. They tend to increase even in recent years, while the mean and maximum temperatures show a decrease. In particular, they also tend to increase after 1930 and decrease at a slower rate than the other temperatures, starting from 1960. A similar trend is also found in other Italian cities. In particular, trends have been analysed applying the same techniques to data referring to the cities of Milan (45°25′ N; 9°10′ E) and Parma (44°48′ N; 10°20′ E) both with centuries old records. In both cases, the minimum temperature behaved in an opposite way to the maximum one (Fig. 4a, b). It is significant that if, as is likely, the difference is due to the growth of the city, the effect on Parma, which has a population of only 200,000 inhabitants, is obviously smaller than that on the Rome and Milan data. A similar comparison has also been made with trends referring to Paris (Detwiller, 1970). In this case, it was also observed that the minimum temperatures tended to increase markedly with respect to the maxima, even when the latter tended to decrease after 1950.

3.3. *Urban heat island*

The differences in the maximum and minimum temperature trends may be interpreted as a long-term variation due to the city's growth and the result of increasing urban temperature due to human causes. This effect is more apparent in the minimum temperatures than in the maxima since, as is well-known (Oke, 1974; Landsberg, 1981), the urban heat island effect is more noticeable during the night than during the day. This has been demonstrated for the city of Rome, in particular by means of a climate analysis in which the trend in the difference between urban and rural temperatures $T_U - T_R$ was examined and which revealed the existence of an effect on the minimum temperatures (Colacino and Lavagnini, 1982). Minimum urban temperature increase is usually explained by linking the temperatures with the resident population, a parameter that reflects the size of the city itself. In the case of Rome, the correlation analysis was carried out using annual data referring to the resident population from 1860 until 1978, together with the corresponding minimum temperatures. Regression was carried out using relations of the following type taken from the literature

$$T_{min} = a + b\ {}^{10}\log P, \quad (1)$$

$$T_{min} = a + bP^{0.25}. \quad (2)$$

Table 2 shows the data referring to the two linear regressions with the corresponding errors. The two distribution trends are given in Figs. 5a and 5b, which show the straight lines that fit the data by using formulae (1) and (2), respectively. It can also be seen that the values of a in (2) represent the temperature that would occur in the zone as $P \to 0$.

Table 2. *Temperature-population correlation parameters*

Correlation type	a	b
$T_{min} - {}^{10}\log P$	5.798 ± 0.610	0.937 ± 0.104
$T_{min} - P^{0.25}$	9.663 ± 0.184	0.054 ± 0.006

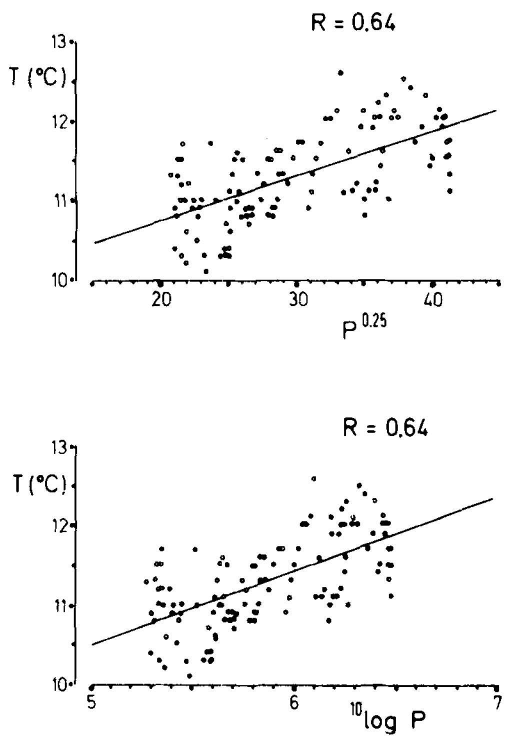

Fig. 5. Regression analysis results obtained for the correlation between temperature sequence and population number following the logarithmic (on the bottom) and fourth root (on the top) model.

This value is in agreement with the mean minimum values, i.e. 9°–9.5 °C, found in the rural areas around Rome (see Colacino and Lavagnini, 1980).

In conclusion, the heat island effect may be said to partially explain the increase in minimum temperature as a long-term variation affecting the local micro-climate.

4. Spectral analysis and solar cycle correlation

After the trend analysis showing temperature data set behaviour on a century scale ($\gtrsim 50$ years), the data are processed using Fourier techniques in order to analyse the spectral characteristics of the short-term fluctuations ($\lesssim 50$ years). Particular attention was paid to the effects present in the air temperature which could be due to the solar cycle effect. The power spectrum of the temperature series x_t was computed using the classical relationship (see, for example, Otnes and Enochson, 1972, or Bath, 1974)

$$E(f_k) = 2\,\Delta\tau\left(\phi_0 + 2\sum_{\tau=1} \phi_\tau \cos\frac{\pi k\tau}{M} + \phi_M \cos \pi k\right), \qquad (3)$$

where the frequency f_k (in cpy) corresponds to the quantity $k/2M\,\Delta t$, with $k = 0, 1, 2, \ldots, M$, and ϕ_τ is the autocovariance corresponding to the time lag τ:

$$\phi_\tau = \frac{\sum_{1}^{N-\tau} x_t x_{t+\tau}}{N-\tau}, \qquad \tau = 0, 1, 2, \ldots, M. \qquad (4)$$

The power spectrum thus obtained was smoothed by a Hanning function in order to reduce signal windowing effects.

This spectral analysis was preceded by data filtering using a high-pass Ormsby filter ($f_c = \frac{1}{320}$ cpy, $f_r = \frac{1}{40}$ cpy) in order to eliminate the long-period trend. The spectrum for the mean temperatures is shown in Fig. 6 where the upper and lower limits of the 90% confidence-interval of the equivalent Markovian process are also indicated. As, on the basis of this assumption, there is a 90% probability that the data of the spectrum are between these limits, the peak around 11 years is statistically significant.

As this peak could be representative of an influence of the solar cycle on the air temperature, the analysis was repeated using the maximum entropy method as well. This method is generally applied in order to enhance narrow frequency lines

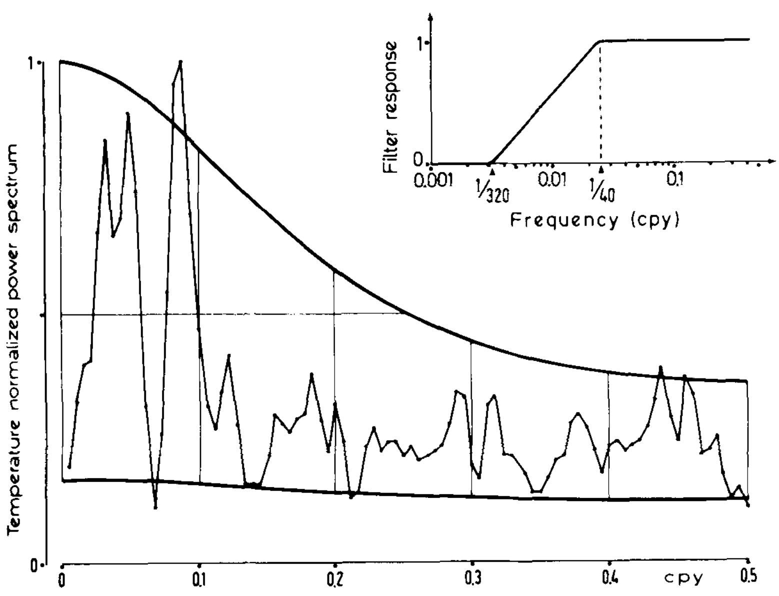

Fig. 6. Power spectrum of the mean temperature data filtered using a high-pass filter as shown at the top of the figure. The interval between the two thick lines represents the 90% confidence limit of the equivalent Markovian process.

in the signals (Ulrych and Bishop, 1975). In this case, spectral evaluation is carried out through the expression:

$$E(f) = P_{M+1}\,\Delta t \Bigg/ \left| 1 + \sum_{1}^{M}{}_{k}\, \gamma_k \exp\,(-i2\pi f k\,\Delta t) \right|^2, \quad (5)$$

where P_{M+1} is the power output of the prediction error filter Γ

$$\Gamma = \begin{pmatrix} 1 \\ \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_M \end{pmatrix} \quad (6)$$

linked to the matrix R of the autocovariances ϕ_m ($m = 0, 1, 2, \ldots, M$) by the expression

$$R\Gamma = P \quad (7)$$

where

$$R = \begin{pmatrix} \phi_0 & \phi_1 & \cdots & \phi_{M-1} & \phi_M \\ \phi_1 & \phi_0 & \cdots & \phi_{M-2} & \phi_{M-1} \\ \vdots & \vdots & \vdots\vdots\vdots & \vdots & \vdots \\ \phi_M & \phi_{M-1} & \cdots & \phi_1 & \phi_0 \end{pmatrix} \quad (8)$$

and

$$P = \begin{pmatrix} P_{M+1} \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}. \quad (9)$$

A forward-backward algorithm from the Andersen (1975) flow-chart has been used with filter length M estimated from the characteristic correlation time of the data series (Rovelli, 1982; Rovelli and Vulpiani, 1982).

In Fig. 7 the maximum entropy spectra obtained for both mean air temperature and sunspot number are shown. The sunspot number data refer to the period 1749–1951 and have been taken from Kiepenheuer (1953).

By comparing the two graphs, it is apparent that both series display the highest peak around 11 years. It can thus be concluded that, in the band

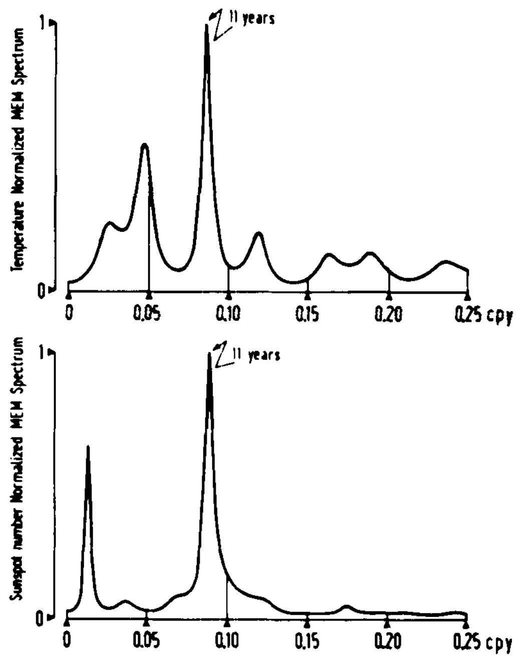

Fig. 7. Bottom: maximum entropy spectrum of sunspot number sequence. Top: maximum entropy spectrum of the mean temperature data after high-pass filtering as shown at the top of Fig. 6. Both spectra display a high peak around a period of about 11 years.

between 2 and 40 years, the main quasi-period of the air temperature is 11 years and is probably linked to the solar cycle. In the temperature spectrum, a peak of around 19 years is also present and could perhaps be related to the lunar-nodal mode, which has a period of 18.6 years (see Currie, 1979 and 1982).

However, since the maximum entropy spectrum, which is quite effective in localizing the lines by means of narrow peaks, does not allow the amplitude of the periodic oscillation detected to be evaluated, a numerical band-pass filter with unitary gain between $\frac{1}{10}$ cpy and $\frac{1}{12}$ cpy (top of figure) was made. The temperature data processed using this numerical filter gave an output whose behaviour is shown in Fig. 8. It can be seen how the maximum 11-year temperature oscillation occurs around the years 1810–1830 with a peak-peak amplitude of about 0.8 °C. The phase between the solar cycle y_t and the air temperature x_t was also investigated by means of correlation analysis between the two signals. Fig. 9 shows the behaviour of the normalized cross-variances

$$\psi_\tau = \frac{1}{N-\tau} \frac{\sum_{1}^{N-\tau}{}_t\, y_t x_{t+\tau}}{\sqrt{\left(\frac{\sum_1^N{}_t\, x_t^2}{N}\right)\left(\frac{\sum_1^N{}_t\, y_t^2}{N}\right)}}. \tag{10}$$

The periodicity of the cross-variance sequence is 11 years and a 6-year phase shift is apparent, indicating that the signals are in phase opposition. It is also significant that the envelope of the cross-covariances does not decrease strongly with increasing time lag, which confirms the high stability of the correlation between the two signals.

5. Concluding remarks

It is evident that in a city as large as Rome, the air temperature is determined not only by natural climatological effects, but is also affected by human activities, in particular by the urban heat island effect. From the results above, the following

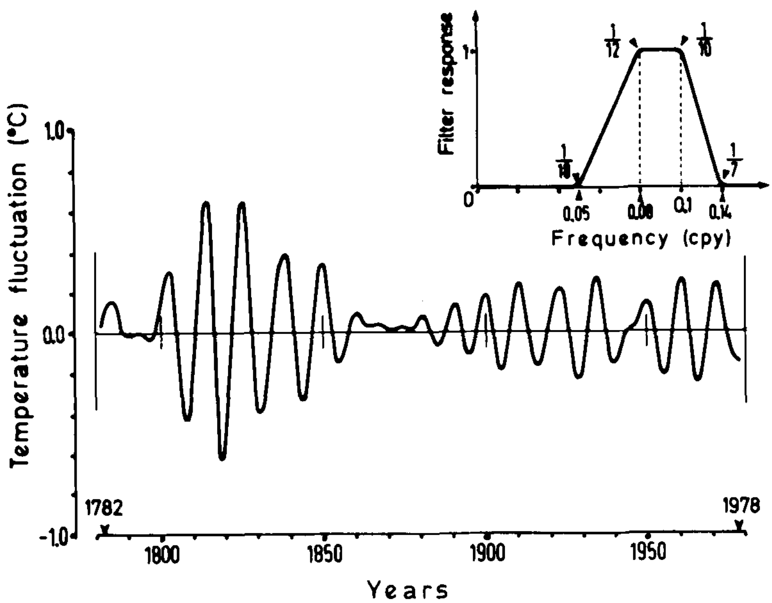

Fig. 8. The 11-year temperature fluctuation in Rome obtained by numerical band-pass filtering (the frequency response is shown at the top of the figure).

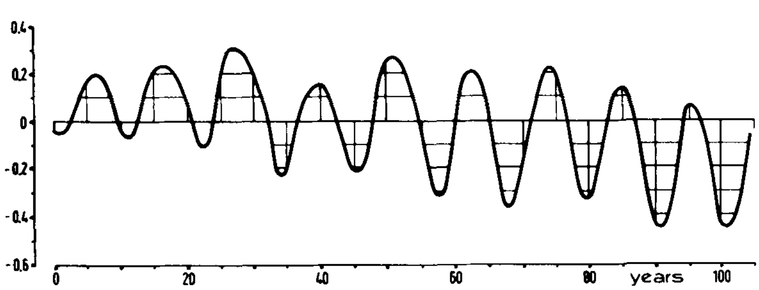

Fig. 9. Cross-variance estimates between air temperature data and sunspot number sequence: a periodicity of about 11 years and a 6-year phase shift between the two signals are evident.

conclusions emerge, concerning natural and human influences on the temperature:

(i) the mean and mean maximum temperatures show different behaviour patterns than the mean minimum temperature. This can be explained by the fact that the growth of the city and the human activities connected with it have created a well-defined local microclimate;

(ii) this effect can be quantified, and the Oke formula (Oke, 1974), which links the minimum temperature with the fourth root of the population number is confirmed;

(iii) the analysis of the trends confirms the patterns found by other researchers, which can be summarized by a decrease of temperature from 1810 till 1880, an increase in the following years to 1950 and, finally, a new decrease in more recent years;

(iv) the spectral analysis, carried out by standard power spectrum techniques and the maximum entropy method, shows the existence of a clear peak around 11 years, which is probably connected to the solar cycle. This link is confirmed by cross-correlation analysis.

6. Acknowledgements

The authors are grateful to the Director of the "Ufficio Centrale di Ecologia Agraria", who furnished the data from 1911 to 1975. Many thanks are due to Professors A. Berger and M. Ghil for their useful suggestions and comments. This work is supported by the CEE grant no. CLI-019-I(S).

REFERENCES

Andersen, M. 1974. On the calculation of filter coefficients for maximum entropy analysis. *Geophysics 39*, 69–72.

Bath, M. 1974. *Spectral analysis in geophysics*. Elsevier Scient. Publ. Co., Amsterdam.

Bücher, A. 1981. Cycle solaire et température. *J. Rech. Atmos. 15*, 149–156.

Colacino, M. and Lavagnini, A. 1980. Elementi di climatologia della bassa Valle del Tevere. IFA Tech. Rep. no. 14, Istituto di Fisica dell'Atmosfera—CNR—Rome p. 113.

Colacino, M. and Lavagnini, A. 1982. Evidence of the urban heat island in Rome by climatological analyses. *Arch. Meteorol. Geophys. Bioklimatol. Ser. B, 31*, 87–97.

Currie, R. G. 1974. Solar cycle signal in surface air temperature. *J. Geoph. Res. 79*, 5657–5660.

Currie, R. G. 1979. Distribution of solar cycle in surface air temperature over North America. *J. Geoph. Res. 84*, 753–761.

Currie, R. G. 1981. Solar cycle signal in air temperature in North America: amplitude, gradient, phase and distribution. *J. Atmos. Sci. 38*, 808–818.

Currie, R. G. 1982. Evidence for 18.6 yr M_N term in Japanese air pressure and geophysical implications. *Geophys. J. R. Astron. Soc. 69*, 321–327.

Detwiller, J. 1970. Évolution séculaire du climat de Paris (influence de l'urbanisme). Mem. Meteorologique Natl. no. 52, Meteorologie Nationale—Paris p. 83.

Eredia, F. 1911. *Il clima di Roma*. Tipografia Bertero, Rome.

Garstang, M., Tyson, P. D. and Emmitt, G. D. 1975. The structure of heat island. *Rev. Geophys. Space Phys. 31*, 139–165.

Hoyt, D. V. 1979. Variations in sunspot structure and climate. *Clim. Change 2*, 79–92.

Kiepenheuer, K. O. 1953. Solar activity. In *The Sun* (Ed. G. P. Kuiper), London, England: The University of Chicago Press, 322–465.

Landsberg, H. E. 1981. *The urban climate*. Intern. Geophys. Series vol. 28, Academic Press, New York.

Mass, C. and Schneider, S. H. 1977. Statistical evidence of the influence of sunspots and volcanic dust on long-term temperature records. *J. Atmos. Sci. 34*, 1995–2004.

Oke, T. R. 1974. Review of urban climatology (1968–1973). WMO Tech. Rep. no. 134, Geneva, Switzerland.

Oke, T. R. 1979. Review of urban climatology. WMO Tech. Rep. no. 169, Geneva, Switzerland.

Ormsby, J. F. A. 1961. Design of numerical filters with application to missile data processing. *Assoc. Comp. Mach. J. 8*, 440–446.

Otnes, R. K. and Enochson, L. 1972. *Digital time series analysis*. Wiley–Interscience Publication, New York.

Rovelli, A. 1982. On the information time scale of geophysical records in maximum entropy spectral analysis. IEEE Trans. on Geosci. and Remote Sensing, vol. GE-20 no. 2, 158–161.

Rovelli, A. and Vulpiani, A. 1982. Characteristic correlation time as an estimate of optimum filter length in maximum entropy spectral analysis. *Geophys. J. R. Astron. Soc.*, in press.

Schönwiese, C. D. 1981. Solar activity, volcanic dust and temperature: statistical relationships since 1160 A.D. *Arch. Meteorol. Geophys. Bioklimatol. Ser. A, 30*, 1–22.

Ulrych, T. J. and Bishop, T. N. 1975. Maximum entropy spectral analysis and autoregressive decomposition. *Rev. Geophys. Space Phys. 13*, 183–200.