ANALYSIS OF THE LONG-TERM PRECIPITATION SERIES AT ATHENS, GREECE

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Abstract. In this paper, the characteristics of the long-term precipitation series at Athens (1858–1985) have been statistically analyzed. This study covers both the history and the analysis of the data. The ten-year mean amounts, the monthly and annual amounts averaged over the intervals 1858–1890, 1891–1985, 1951–1980, 1858–1985, the mean number of hours of precipitation and the precipitation intensity are given. The analysis of long-term time series of climatic data (in particular precipitation) is a useful tool for the study of past climate. Different statistical techniques are used in order to depict monthly, seasonal and annual variations, as well as trends, periodicities and recurrence intervals of the amount, intensity and number of precipitation days. The analysis reveals many interesting characteristics. These characteristics of the precipitation regime are extended to a time scale from seasonal variation to a semi-secular trend. The study of such long-term series may be helpful not only in practical applications of rainfall, but also for explaining the possible physical or anthropogenic mechanisms of climatic fluctuations and tendencies. The series of precipitation at Athens is one of the longest in south-eastern Europe.

1. Introduction

Climatic change is of inestimable importance to the human race. The climate has determined the areas of the world in which the major civilizations have developed, and any change in climate will necessarily impose changes in the way of life of the people affected. The importance of climate change grows with time, for as populations have grown, crop production has been maximised by developing specialised species which are best suited to the prevailing climate, and which are therefore more sensitive to any changes in climate.

Many scientific efforts have been devoted in recent years to a better understanding of the climatic system and to unraveling the history of regional and global climates. Although much progress has been made there still remains a number of unsolved problems. In the field of research of climatic change, and in approaching a forecasting of the tendency to be expected in the future, one must distinguish between effects acting on different time scales, e.g. short- and long-term climatic changes due to natural causes, and changes attributed to anthro-

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pogenic activity (Spar and Ronberg, 1968; Reidat, 1971; Khemani and Ramana, 1973; Ackerman and Changnon *et al.*, 1978; Seibel, 1980; Witter, 1982; Flohn and Fantechi, 1984). For example, the impact of precipitation on climate and history is not only limited to extreme events remote in space and time, e.g. end of civilizations attributed to famines caused by drought conditions (Carpenter, 1966; Camuffo, 1984), but is also responsible for many modern changes of the natural environment.

In recent years several studies concerning analyses of long-precipitation series from single stations have been published by some researchers (e.g. Wales-Smith, 1971; Manley, 1973; Goldreich and Manes, 1979; Palumbo and Mazzarella, 1980; Hameed *et al.*, 1983; Camuffo, 1984; Colacino and Purini, 1986). A renewed interest has been expressed in sun-weather relationships (Herman and Gordberg, 1978; Mitchell *et al.*, 1979; Currie, 1981a; Gregory, 1982; Gilliland, 1982; Gribbin, 1982; Pittock, 1983). The reconstruction of past climates is also based on a variety of evidence, such as archeological, geological (Shuurmans, 1980). However, the data obtained from long climatological measurements are an important source of information. So, an increasing interest is being shown in the climatic historical studies by some authors (Peczely, 1974; Granger, 1977; Colacino and Rovelli, 1983; Camuffo, 1984; Brazdil *et al.*, 1985). This is more evident with reference to the development of mathematical models, whose validation requires the proper use of quantitative data on climatic variations.

Precipitation measurements are known to have been made in the city of Athens for well over 140 yr. A few papers are available on aspects of Athens precipitation (Livathinos, 1933, 1934; Karapiperis, 1957; Katsoulis *et al.*, 1976).

Some historical and instrumental series exist in Greece (e.g. Athens, Thessaloniki, Heraklion, Larissa, Corfu) and a few of them have been analysed by Greek Climatologists (Eginitis, 1907; Mariolopoulos, 1938, 1960; Flocas, 1974; Metaxas, 1974; Repapis, 1986).

This paper follows an analysis of the air-temperature in Athens (Katsoulis and Theoharatos, 1985, Katsoulis, 1987) and studies the precipitation series collected by the Meteorological Institute of the National Observatory of Athens (hence-forth MINOA). For the precipitation record, an attempt is first made to assess the following factors:

(i) Homogeneity of the record. The data have been taken at several different sites over the period of record.

(ii) Quality of the observations. The measuring period had different observers.

(iii) Change in the environment near the recording site. The station has distinct changes in the immediate surroundings, e.g. tree growth and urbanization.

(iv) Type of instrumentation. Early observations at some places are taken with non-standard instruments.

The basic aim of this study is to investigate characteristics of the precipitation regime and the feasibility of predicting long-term changes of rainfall in Athens. In order to obtain further information about recent microclimatic changes in the urban area, an analysis of the secular variations of rainfall intensity has been worked out.

In particular, this paper is devoted to the history and the analysis of the data: after a short review on the data set used, a first series of results is shown based on standard statistics. Then, trends, periodicities and other variations of precipitation are discussed. Filtering is also applied and the resulting trends are commented. Finally, spectral analysis shows the existence of several cycles.

2. History of the Long-Term Series of Precipitation at Athens

Precipitation measurements over the city of Athens have existed since 1839. Continuous and systematic observations though, did not start until 1858. The period therefore, for which there exist continuous and regular precipitation observations is from 1858 to date (128 yr) (see Appendix). Since 1839 the observations were taken at different locations within Athens all of which were within 2 km of each other, as indicated in Table I and Figure 1. No change of the site of measurements took place between 1890 and to date (1986). Since 1890, the precipitation measurements have been carried out at MINOA on a hill ($\varphi = 37^\circ\, 58'$ N, $\lambda = 23^\circ\, 43'$ E, h = 107m).

The unbroken series of rainfall was accurately documented in the registers of the original data and observers' diaries and notebooks and was reviewed by some authors, most of whom had worked in (MINOA) where the registers are kept (Peytier, 1837; Fraas, 1847; Vouris, 1848; Papadakis, 1857; Schmidt, 1884; Vourlis, 1889; Eginitis, 1907; Mariolopoulos, 1960). The history can be summarized as follows: The observations during the years 1858–1862, were performed by the German Astronomer Schmidt and appeared in "Publications de

TABLE I: Periods, locations and altitudes of the precipitation measurements

Period	Location	Altitude (m a.m.s.l.)
1839–1842	Aghia Irene	$h = 79.1$
1847–1848 Meteor. Institute	National Observatory of Athens (MINOA)	$h = 107.1$
1853–1858 Meteor. Institute	National Observatory of Athens (MINOA)	$h = 107.1$
1858, Dec. 2–1859, Aug. 12	Hotel Byzantine (center of city)	$h = 84.1$
1859, Aug. 13–1861, Sept. 6	Dedes Garden (center of city)	$h = 77.0$
1861, Sept. 7–1863, Sept. 12	Anagnostakis Garden (near Palace)	$h = 103.3$
1863, Sept. 13–1871, May 15	Skapessos Garden (Lykabetus str., center of city)	$h = 102.7$
1871, May 16–1871, Aug. 15	Demopoulos Garden (center of city)	$h = 110.9$
1871, Aug. 16–1877, Sept. 8	Igglessis Garden (North of Palace)	$h = 103.1$
1877, Sept. 9–1866, Oct. 1	Schmidt Garden (near Lykabetus Hill)	$h = 109.6$
1866, Oct. 2–1890, Sept. 10	Vourlis Garden (near Lykabetus Hill)	$h = 124.1$
1890, Sept. 11–to date Met. Inst.	National Observatory of Athens (MINOA)	$h = 107.1$

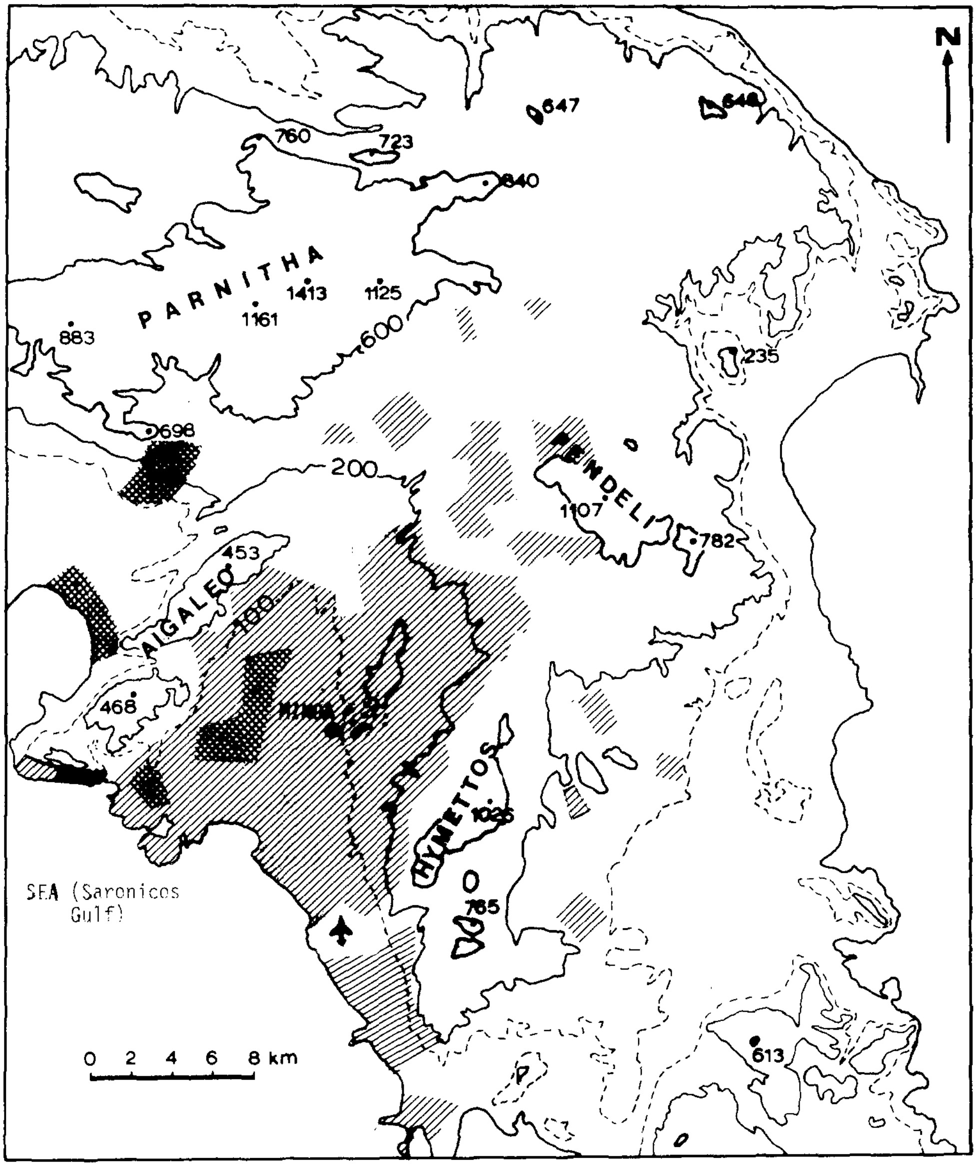

Fig. 1. Map of the Athens area showing the locations of the early precipitation stations (the dots near MINOA) in Athens (period 1858–1890) and the station of the Meteorological Institute of the National Observatory of Athens (MINOA) (1890–to day). The 100 m (dashed), 200 m (solid) and 500 m (heavy solid) contour lines are also indicated.

l'Observatoire d'Athens, IIeme Serie, Vol. I, II, III, 1884". For the period 1863 to 1870, the observations as well as their processing and archiving were done by professors A. Vourlis and D. Eginitis; they were taken by the German Government and were kept in the archives of the Potsdam Observatory. From 1871 to 1884, the observations were performed by five different observers; after they had

TABLE II: Mean monthly and annual values of precipitation (mm) for the old sites (1858–1890), the permanent site (MINOA) (1891–1985), and the current 30 year (1951–1980) values, at Athens

	J	F	M	A	M	J	J	A	S	O	N	D	Y
Old sites	51.8	37.0	34.3	20.7	19.6	17.2	7.3	9.2	14.1	43.5	73.3	61.6	393.3
Permanent site	56.1	41.2	35.9	21.9	21.6	13.0	5.8	7.7	15.3	47.6	64.1	69.6	399.8
Current	55.5	42.9	37.9	23.3	23.2	8.7	3.8	5.2	15.8	61.6	55.8	65.2	398.8

been analysed by those observers, they were also kept at the Potsdam Observatory.

During the years 1884 to 1890, the observations were made by two observers and were published in the 'Greek Government Paper'. Since 1890 the meteorological observations (and among these the precipitation measurements) have been taken at MINOA.

These long precipitation records need to be adjusted because errors in the data were caused by non-standard measuring techniques, urbanization, sheltering, relocation of the station etc.. Table II gives the monthly means and annual totals for all old sites, the permanent site, and the currently used (1951–1980) values.

The effect of removal on the precipitation records (1858–1890), has been determined by the mean differences obtained between the old sites and the new permanent site (1890–1985) period. It was found to be 6.5 mm, annually. No corrections for removals of the station have been applied in the statistics given in the sections below because it is felt that corrections are small, insufficiently known.

The first precipitation gauge used in Athens (1858–1890) consisted of a square metal vessel with catchment area of a French square foot (32.5 cm inside). During the period 1891 to 1892, a gauge with a cylindrical metal vessel was introduced. This gauge had a circular collecting area of 200 cm^2. The observations were taken twice a day.

Since 1893, a new rain-gauge with a circular rim was used, with a catchment area of 1000 cm^2 (Tonnelot type) and a Richard-type rain-gauge recorder as well. A comparison between all types of rain-gauges has been carried out by Mariolopoulos (1938), who concluded that the measurements with smaller gauges were as accurate as those with the larger ones. It was found that the new gauges with a rounded rim collected about 2% more rain than the old one, and 4% more snow and hail. The heights of the rim of the gauges above ground varied between 1.20 m to 1.70 m.

The time interval of 1894 to date (92 yr) during which the precipitation observations are taken at the same site, using both instruments of direct measurements as well as a recorder, can be regarded as a period of homogeneous observations, the only variables being the observers, and some changes in the environment near the recording site, such as tree growth and urbanization.

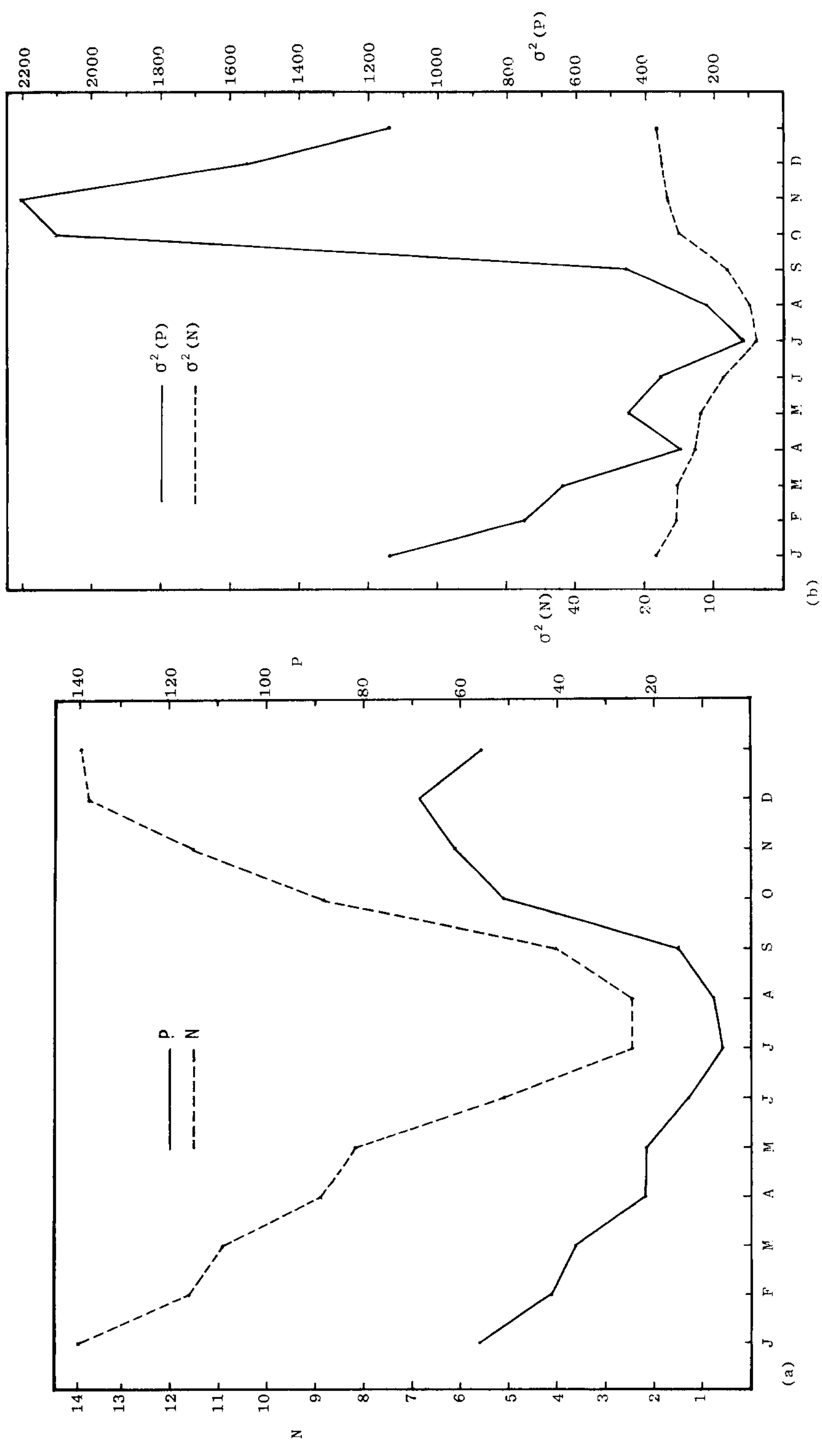

Fig. 2(a, b). Monthly values of amount (P) and number of precipitation days (N) and their variances σ^2(P) and σ^2(N).

In order to test the homogeneity of the series, the well-known "Run Test" has been applied. The test showed that the precipitation amount and the intensity series are homogeneous, but precipitation days are inhomogeneous (at a 95% significance level).

3. Precipitation Characteristics

3.1. *Monthly and Seasonal Variations*

Precipitation in Athens, on the southeastern part of the Greek Peninsula, is characterized by a great temporal (and spatial) variability. This is due to the complicated physical processes of its origin, which are influenced by synoptic circulation, geographical and local topographical factors (mountains, plains and the sea) and their effects on the mesoscale circulations. It is not what one would expect on the basis of the tracks of the synoptic disturbances only. During the summer, fair weather generally prevails in southern Greece, due to the Azores anticyclone, or because of the Siberian high pressure extension. Showers and thunderstorms occur rarely during the daytime, especially in the afternoon, when the insolation produces strong superadiabatic lapse rates and instability phenomena. In winter, the weather is characterized by travelling weather disturbances which pass north of the area of Athens causing cold and warm fronts to sweep alternately across the Greek Peninsula. Southern Greece and Athens in particular, have a modal rainfall course during the year with maximum in late autumn and early winter and minimum in summer. It appears that the climatological amounts of precipitation result mainly from the winter and autumn precipitation. The number of precipitation days (N) and the amount (P) at Athens, together with their variances σ^2(N) and σ^2(P) are shown in Figure 2. One can note that σ^2(N) and N are in phase and experience a similar annual march. They have one maximum falling in December and January. Particularly, the number of precipitation days experiences the minimal variability in the warm season which is characterized by the regularity of the Azores anticyclone and/or the 'Etesian winds system' (Weather in the Mediterranean, 1965; Furlan, 1977). The other seasons are more subject to the occurrence of synoptic disturbances. Similarly, σ^2 (P) has one maximum (in October and November). This is also in phase with P and seems to have a very high variance during October and November, because of the active change of season.

The correlation between pairs of months is very low, so that in the course of the year it is difficult to make any prediction on the basis of the knowledge of the past amount of precipitation, as shown in Table III. The insignificant correlation between pairs of months can be attributed to the relative independence among the synoptic conditions characterizing the precipitation in each season. This is clearly shown by the low values of the correlation coefficients, sometimes

TABLE III: Correlation between the amounts P of the precipitation, for the different pairs of months (r)

J	1.00											
F	0.08	1.00										
M	0.06	0.18	1.00									
A	0.04	0.05	-0.08	1.00								
M	-0.04	0.05	-0.07	0.03	1.00							
J	0.07	0.06	-0.07	-0.15	0.06	1.00						
J	0.00	0.03	0.01	0.04	0.06	0.05	1.00					
A	0.01	0.04	0.00	0.17	-0.04	0.02	0.02	1.00				
S	-0.08	-0.06	-0.11	0.01	-0.08	0.06	0.08	0.02	1.00			
O	-0.01	-0.04	-0.08	0.14	0.25	0.03	0.01	0.07	0.04	1.00		
N	-0.06	-0.04	0.01	0.08	-0.05	0.05	0.08	-0.05	0.02	0.14	1.00	
D	0.08	0.11	0.09	0.04	0.01	-0.07	0.02	-0.04	-0.04	-0.10	-0.03	1.00
	J	F	M	A	M	J	J	A	S	O	N	D

Significance levels
$r_{0,05} = 0.20$
$r_{0.01} = 0.26$

slightly higher for pairs of consecutive months showing only a modest steadiness of the same synoptic situation.

3.2. *Hours of Precipitation and Intensity*

The period of hourly records chosen for analysis was 1951–1980. The average annual number of hours during which 0.1 mm or more precipitation per hour fell is 330 hr; simple arithmetic shows that it rains (mean annual) only 4% of the time. The mean number of hours of precipitation and also the least and most for each month (unadjusted for the varying number of hours of the months) are given in Table IV.

TABLE IV: Hours of precipitation (1951–1980)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Mean	63	42	46	23	18	5	3	3	10	29	36	52	330
(%) of hours	19	13	14	7	6	2	1	1	3	9	11	16	
Least	28.5	2.4	12.3	2.3	1.3	0.2	0	0	0	0.6	4.4	16.0	
Most	93.1	93.8	72.5	68.1	61.0	22.0	14.7	24.3	27.8	88.3	66.8	115.1	

Examining the average annual intensity per hour for the 30-yr period of 1951–1980, we find the minimum intensity to occur at 11.00 hr while the maximum one at 16.00 hr (Figure 3). A noticeable feature is that the maximum frequency of occurrence comes at the hour ending at 16.00 for most months. The minimum occurs at 11.00 or 12.00 hr and an almost as definite minimum at 02.00.

Harmonic analysis of the 24 values of hourly precipitation frequency showed a modulation of the precipitation with both a diurnal and semidiurnal period.

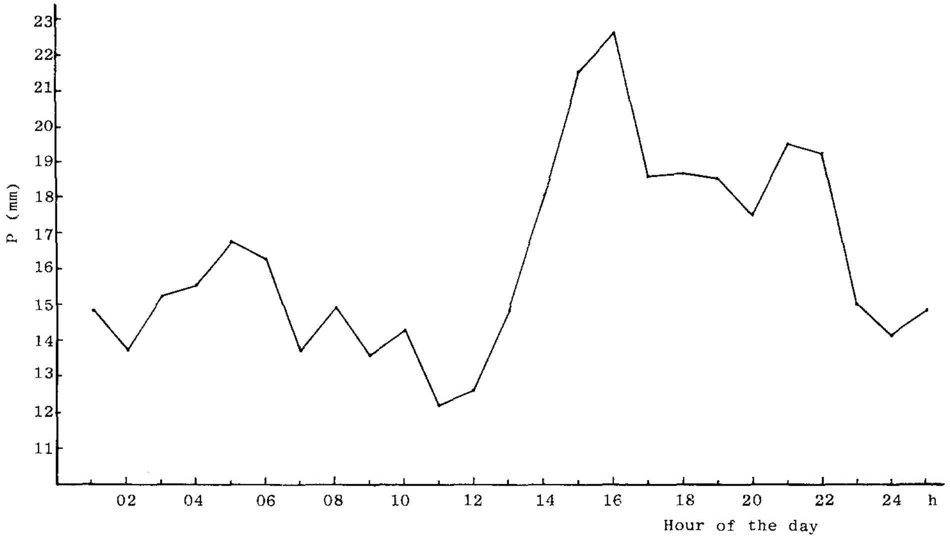

Fig. 3. Hourly intensity of precipitation in mm (1951–1980).

The hourly precipitation events were divided into three intensity categories; from 0.25 to 0.50 mm, 0.51 mm to 2.25 mm and more than 2.25 mm; winter (November–March), summer (June–September) and the total year. Each combination of the intensity and seasonal categories was harmonically analyzed. The first harmonic has a maximum at 23.00 hr and a minimum at 11.00 hr. The second harmonic has two maxima, one at about 05.00 hr and the other at 17.00 hr, while the two minima are at 11.00 and 23.00 hr, respectively. Although individual data samples show some scatter away from these hours, there seems to be no systematic phase shift as a function of intensity or season. Table V below gives the ratios of the amplitudes of the first and second harmonics to the number of precipitation events. This Table shows that the moderate precipitation intensity is modulated in time more strongly than the heavier events.

Figure 4, displays the curves of precipitation intensity (mm h^{-1}) as well as the 30-yr running means of this quantity, for the quality data period 1894–1985. The figure shows that there is a climatic trend of intensity towards decreasing values. Specifically, the mean hourly precipitation for the year indicates that there has been a noticeable though irregular decrease of intensity at MINOA through 1920. The climatological peaks in the annual intensity occurred in the

TABLE V: Amplitudes of 1st and 2nd harmonic

	c_1 mean	c_2 mean
0.25–0.50 mm	0.17	0.16
0.51–2.25 mm	0.20	0.17
more than 2.25 mm	0.08	0.04

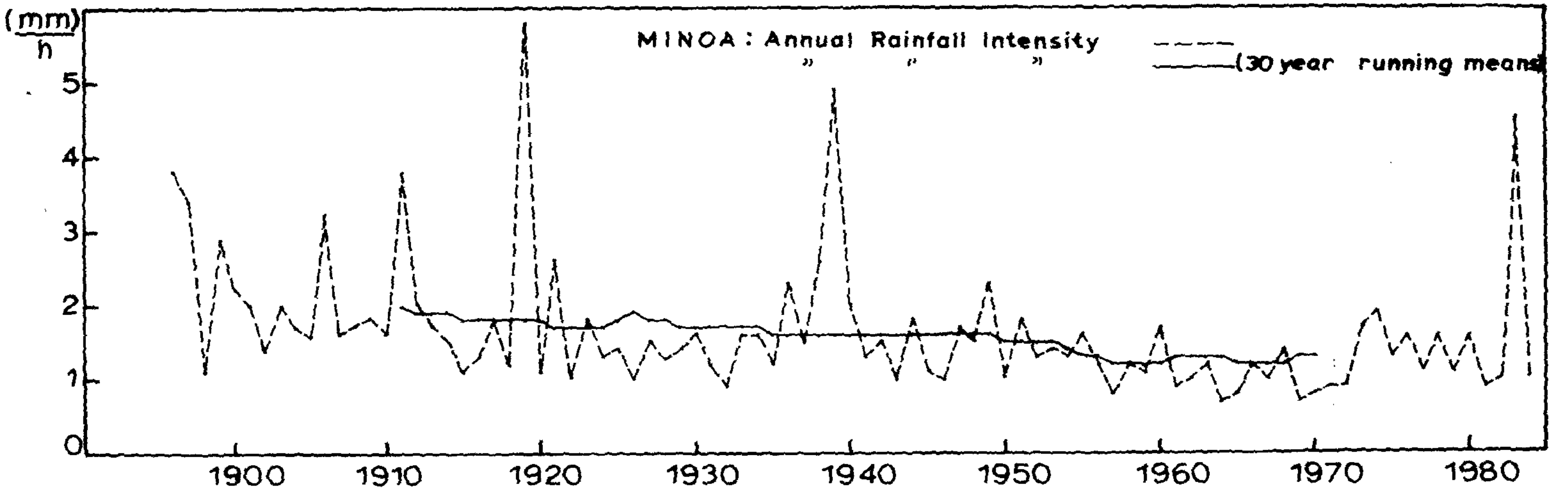

Fig. 4. Trend analysis for the annual rainfall intensity (dashed line) and the 30-yr running means (solid line), at MINOA.

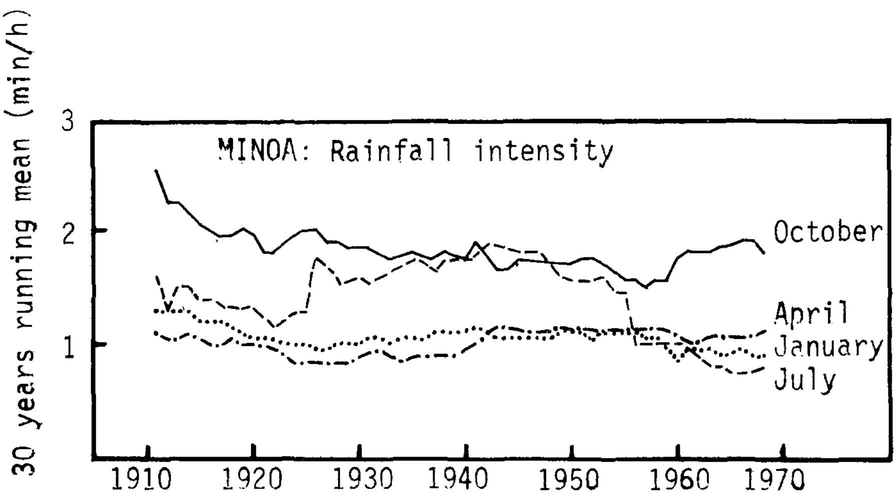

Fig. 5. The 30-yr running means of rainfall intensity for the four typical months.

end of 1910's and 1930's, and in the beginning of 1980's. Figure 5, shows the plots of intensity for the four typical months of the seasons. The general patterns are similar to the annual trend, with the exception of January, where one can see a sudden increase in precipitation intensity from the 1920's up to until the 1950's, followed by a decreasing trend in recent years. The October intensity seems to have peaked in the early part of the 20th century, followed by a declining trend until the 1960's, and then it is rising up again today. This is in accordance with the annual trend of Figure 4. The April and July intensities are rather of constant rate, fluctuating around a mean value.

4. Trend Analysis

4.1. *Methods of Investigation*

The secular variations of the precipitation time-series were studied by statistical methods, e.g. simply from the monthly and yearly values, by means of running means, and numerical low-pass filtering techniques. In the first procedure, the data were collected as daily totals from which the monthly and yearly mean values were obtained; then multiples of 30-yr running means with a 30-yr pass are plotted. This method is only partially successful in removing the oscillations completely. Despite some limitations, the running means comprise a practical method to smooth a time series and to show cyclical patterns. In the second procedure the trends were further studied by means of a numerical filter in order to eliminate the high frequency components. The application of the above methods leads to the following information.

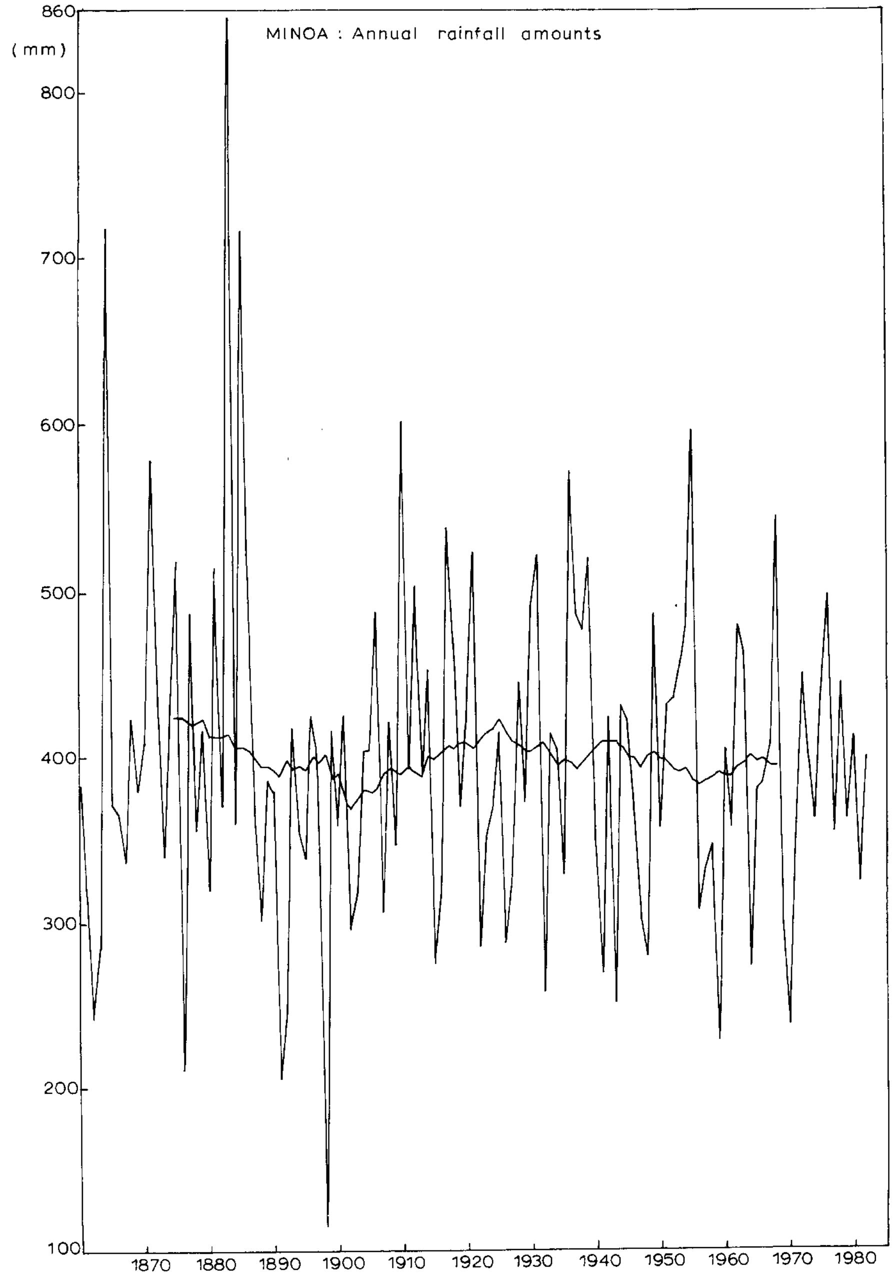

Fig. 6. Annual precipitation (solid line) and 30-yr running mean (dotted line) at MINOA.

4.2. *Mean Annual Precipitation Amounts and Precipitation Days*

The present precipitation mean for 1951–1980 period is 398.8 mm and it falls on an average of 104 days. Using the data for the whole period 1858–1985 the mean annual amount was found to be 400.6 mm, which falls on an average of

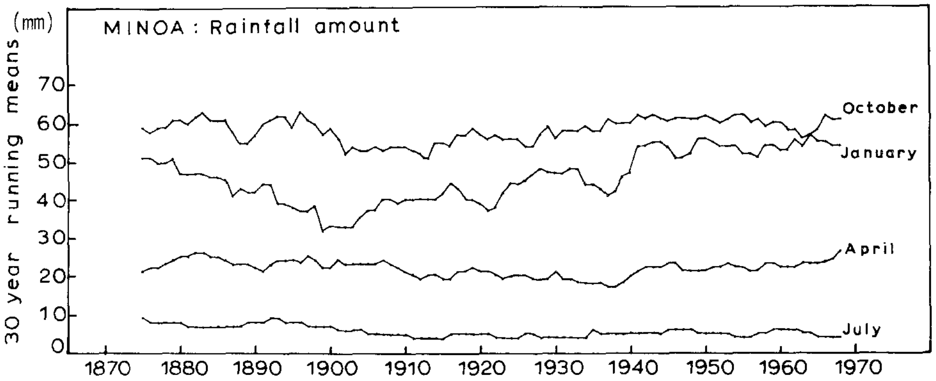

Fig. 7. The 30-yr running means of the January, April, July and October precipitation at MINOA.

104 days. Following Conrad and Pollack's (1952) methodology, the mean deviation of precipitation for the whole 128-yr period is 71.1 mm, the standard deviation is 88.9 mm, and the relative intersequential variability 25%.

Figure 6 shows the annual variation of precipitation at Athens. The annual amount of precipitation varies greatly from year to year (1883 had about 846 mm, while 1898 had less than 116 mm). In the same figure are shown the 30-yr running means of the annual precipitation. There is a trend towards decreasing precipitation up to about 1905, then an increasing trend until 1925, and after that time remains relatively constant with small deviations from the mean annual value of the period. Figure 7 shows the seasonal (through the four months typical of each season) contributions to the 30-yr running means of annual precipitation. The amounts of precipitation for autumn and winter follow a somewhat different trend, but the winter precipitation trend resembles slightly the annual trend of Figure 6. On the other hand, the spring and summer precipitation amounts are much lower.

The amounts show some long-term changes as illustrated by the 10-year

TABLE VI: Ten year means (mm)

1858–1864 (7 yr)	373.8
1865–1874	407.4
1875–1884	440.4
1885–1894	389.1
1895–1904	347.8
1905–1914	421.9
1915–1924	391.7
1925–1934	394.7
1935–1944	415.4
1945–1954	402.6
1955–1964	379.0
1965–1974	383.7
1975–1984	398.3

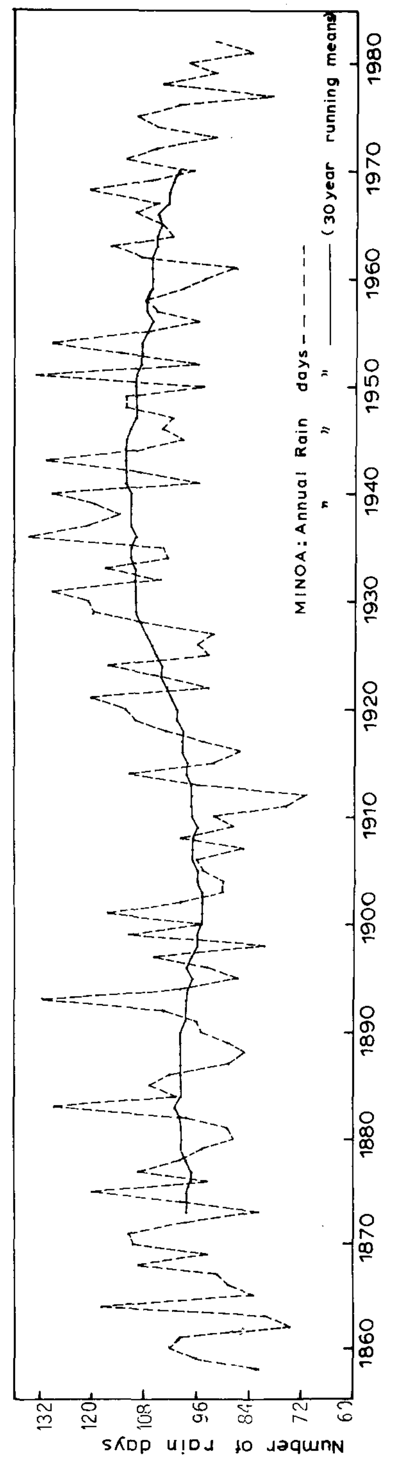

Fig. 8. Trend analysis for the annual totals of precipitation days (dashed line) and 30-yr running means (solid line).

means given in Table VI. Of the 13 pairs of *t*-test statistics computed between the 10-yr means and the long-term mean, the last nine show that the differences are significant (at the 95% level), implying that a real difference existed.

The effects of the urban environment upon the amount of precipitation are difficult to show with the precipitation amount time-series of this study. One can imply, based on the Athens records (even though precipitation trends obtained from single stations are unreliable) that there has been a climatic trend towards a slight increase of precipitation through at least the first 60 yr of the 20th century, followed by a decrease in recent years.

The occurrence of precipitation days was estimated by searching for those days when the daily precipitation was greater than 0.0 mm. Figure 8 shows the number of precipitation days (N) for each year. There is a trend towards increasing precipitation days, from the first part of the 20th century until the 1950's. This period is followed by a decrease towards recent years. This is also shown in the curve for the 30-yr running means plotted in the same figure. The frequency of precipitation days ranges from 71 (in 1912) to 135 days (in 1936). By dividing the whole period of 128 yr into two equal sub-periods, one can see that the second period (1922–1985) recorded more precipitation days than the first one (1858–1921). This may be due to urbanization.

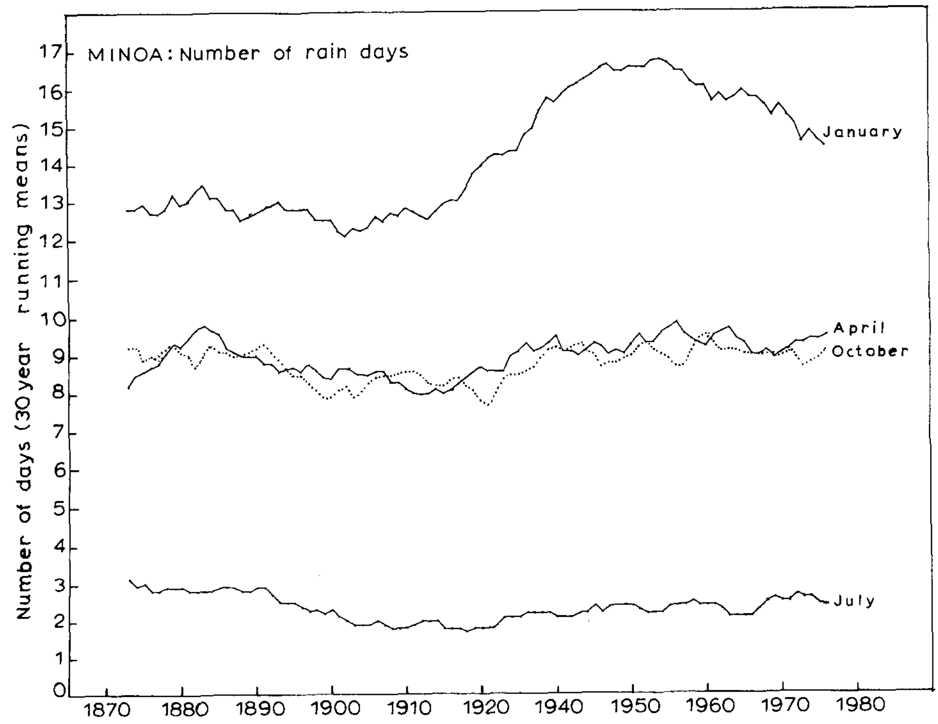

Fig. 9. The 30-yr running means of the January, April, July and October rain days at MINOA.

The distribution of the number of precipitation days shows an approximate 65 year oscillation with two maxima in the early 1880's and 1940's, and two minima in the early 1900's and 1980's. Beginning from 1858 one can note an increase of the variability. The variability of N has higher values during the periods between 1860 to 1900 and 1915 to 1955. The lower values appear during the last decade of the last century and during the most recent 20 yr. Figure 9 shows the 30-yr running means of precipitation days for January, April, July, and October. The numbers for April and October are almost the same and follow similar trend. The winter (January) precipitation days are most numerous and are almost twice those of the transitional seasons represented by the months of April and October. The summer contribution to the annual precipitation days is very low, being due to the local thunderstorm activity of this season. Because of the fact that precipitation shows a marked seasonal character, a monthly analysis has not been attempted by this method (except that of Figure 9). In general, the precipitation amount trends seem to be similar to those of precipitation days, but with different periods. From the figures one can note that nothing can be said at the beginning and the end of the series, where the trends suffer from the truncation of the data. For this reason, it is difficult to draw conclusions about the effects of the general increase of the condensation nuclei in the urban atmosphere of Athens, due to the increased anthropogenic activity during the most recent years.

The existence of real trends of precipitation has been examined by applying the Mann-Kendall (τ-test) test. The annual values of precipitation intensity, and the annual number of precipitation days show significant trends. However, there is no significant trend in the annual and seasonal precipitation amount. For the most recent period (1951–1985) the annual amounts show some noteworthy significant negative trends indicating a general tendency to decreasing values. The increasing tendencies of precipitation of the transitional seasons, which are the unstable parts of the rainy period, seem to be indicative of an urban effect. These slight tendencies of precipitation, may support the theory of the heat island effect, and particularly the mechanical effect of an extended urban area on rainfall enhancement by promoting atmospheric instability. These effects seem to play a role rather than the increasing air-pollution, which may add considerable amounts of condensation nuclei.

4.3. *Trend Analysis Using Low-Pass Filters*

For a detailed description of the time scale characteristics of the Athens precipitation time series, a numerical low-pass filtering technique was applied. By using this technique the trend was further studied in order to estimate the high frequency components. The filtered sequence x_t was obtained by the substitution of each point x_t of the original time series with the weighted mean of the l samples preceding and of the l samples following it. If N is the number of the samples of the annual precipitation (N is the length of the time-series), the trend obtained by the filtering procedure is defined by the expression,

$$x_t = \sum_{k=-l}^{l} h_k x_{t-k} \qquad t = 1, 2, \ldots, N,$$

where h_k is the weight of the x_{t-k} sample. The filter h_k applied in the analysis here is defined by the expression (Ormsby, 1961):

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

with $f_1 = 1/2(f_r + f_c)$ and $f_2 = 1/2(f_r - f_c)$, where f_r and f_c are the roll-off and cut-off frequencies, respectively. In this case, $\Delta t = 1$ yr. The main advantage of this filter is that it has unit gain and zero phase shift. It does not modify both the signal amplitude and the phase shift among the different components. In order to achieve high filtering accuracy it is recommended to select l using the relation,

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

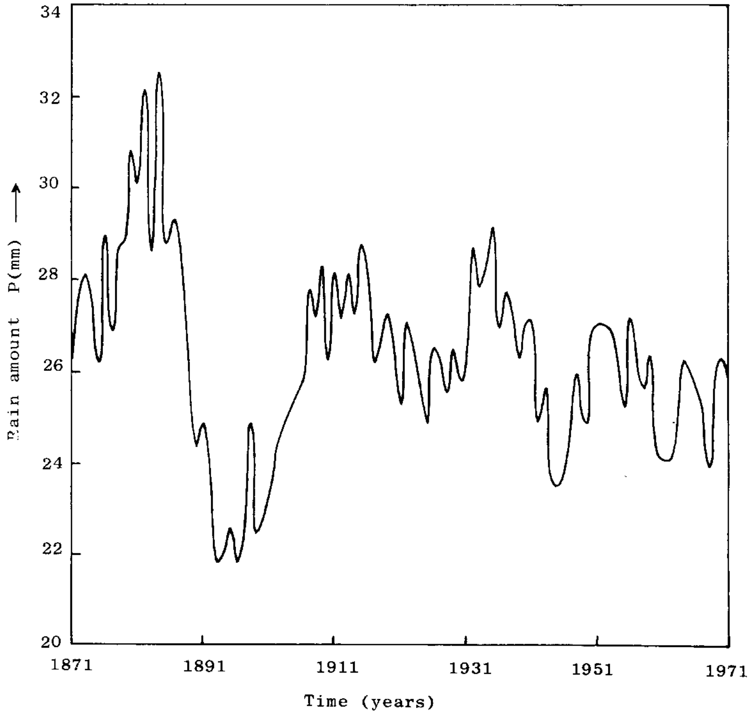

Fig. 10. Trend of all yearly precipitation data smoothed by Ormsby filter, at MINOA.

where $f_N = 1/2\ \Delta t$ is the Nyquist frequency. Consequently, in this case, if we require the elimination of fluctuations with a period of less than 10 yr, we select $f_r = 1/10$ cycles per year and $f_c = 1/100$ cycles per year, which give $l \approx 11$ yr. Finally, it must be emphasized that the results of this filter analysis are less accurate at the initial and final part of the series as the weighted means are affected by the lack of data preceding and following the recording period.

The trend characteristics obtained by this numerical filtering are shown in Figure 10. The presence of dry and wet epochs can be seen, with the maximum around the year 1880. After the year 1905 the wet period tends to be smoothed and this effect was recorded at a South European scale (Goldreich and Manes, 1979; Rao, 1980; Camuffo, 1984; M. Colacino and Purini, 1986). Finally, while in works dealt with air temperature analysis a visible effect of the urban growth on the minimum air temperature time series was detected (e.g. Dettwiller , 1970a, 1978; Oke, 1979; Nkedirim *et al.* 1981; Colacino and Rovelli, 1983; Katsoulis, 1985, 1987), from Figure 10 the urban island effect is not evident on the precipitation amount which presents a pattern affected by the synoptic systems behaviour.

5. Periodicities of Precipitation

The periodicities of the Athens precipitation time-series were attempted by a

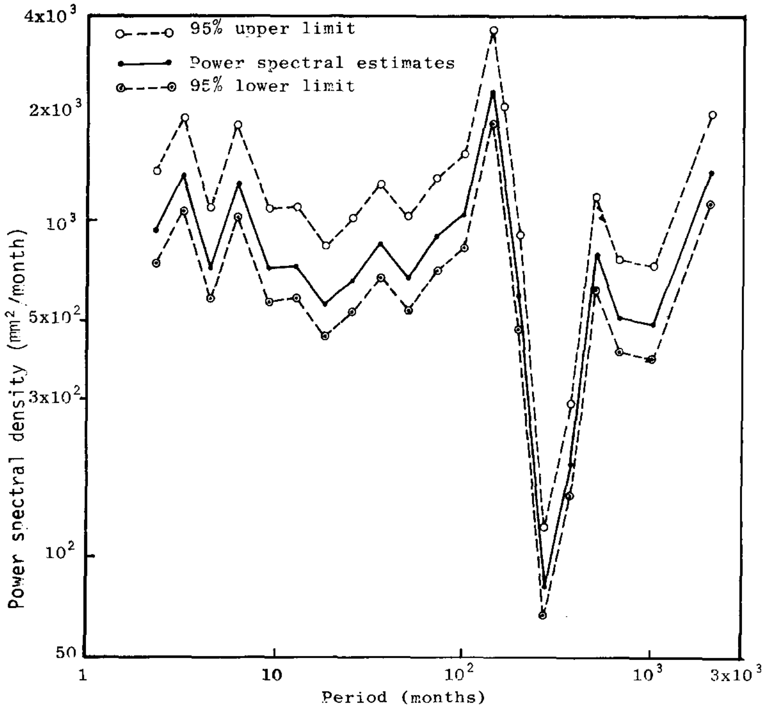

Fig. 11. Precipitation amount power spectrum for all the monthly data, at MINOA.

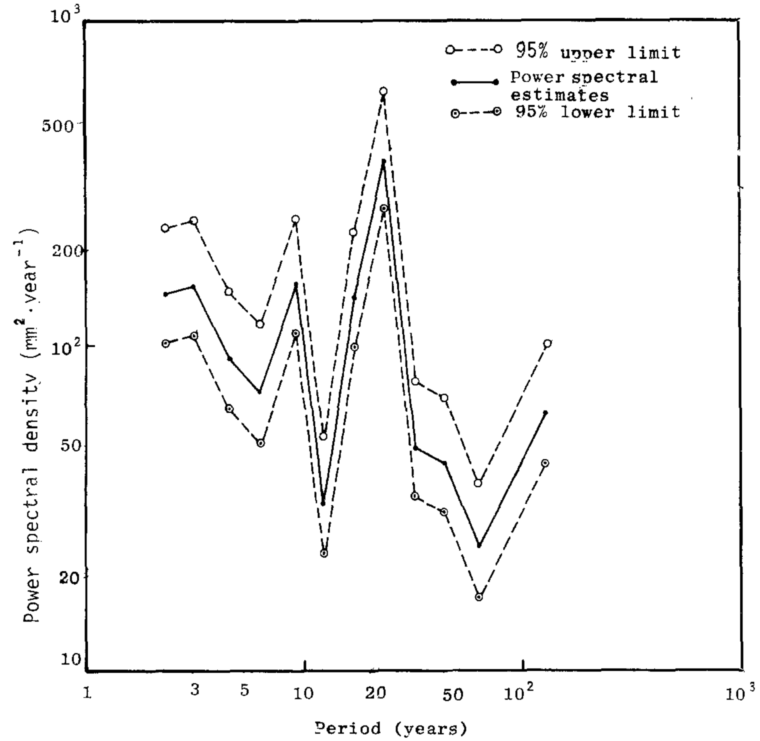

Fig. 12. Power spectrum of precipitation amount for all the yearly data, at MINOA. The upper and lower lines indicate the 95% confidence limits.

few climatologists in the past (Livathinos, 1934, Mariolopoulos, 1937; Karapiperis, 1942, 1957) with controversial results. The doubts have to be attributed to restricted computing capabilities, methods of research, and absence of well-marked oscillations with constant phase. Except for a few irregular correlations with the sunspot cycle showing some spectral peaks in certain regions, any direct relationship with the precipitation remains in doubt (Karapiperis, 1949, 1953; Katsoulis, 1976). On the other hand, non-linear effects due to other astrogeophysical phenomena, may be responsible for single oscillations rather than true periodicities.

The spectral analysis of the data using a Fast Fourier Transform (henceforth FFT) technique was used to reveal cycles in the series. The analysis was applied to both precipitation amount and intensity.

All the monthly data were analyzed first and the derived spectrum shows peaks around 11.7 and 3.5 yr (Figure 11). The periods are probably related to the solar cycle and to the quasibiennial oscillation (QBO) of the zonal wind.

The corresponding spectrum of yearly averaged data shows cycles at about 23.8, 8.7, and 3.1 yr (Figure 12). The 3-yr period can be related to the QBO of the zonal wind, while the 8 yr period is not clearly related to any astrogeophysical phenomena (possibly produced by interaction of the '10–12 yr' cycle with the longer-term cycles (Tabony, 1981; Vines, 1986). Finally, the 23-yr period is usually associated with the double solar cycle (22.2 yr). It must be stressed, however, that the connection between atmospheric phenomena and solar cycle is not generally accepted and is very controversial (Pittock, 1978). Concerning the precipitation behaviour two different findings exist: the first states that no relevant effect of 11-yr solar cycle is present in precipitation data, the second claims instead that the solar cycle disturbance is present (King, 1975; Pittock, 1983; Colacino and Rovelli, 1983; Vines, 1984; Colacino and Purini, 1986).

The analysis was also applied to precipitation amount and intensity data for all months. The results for four typical months and the yearly data are given in Table VII. Generally, the results presented in Table VII show some prominent peaks at 2.0–3.0 and 9.0 yr, but no regular periodicities were found. There were a number of cycles that appeared and disappeared, the most important of which are 3.1 and 23.8 yr in precipitation amount, and 2.4 and 33.3 yr in intensity.

TABLE VII: Significant spectral peaks. Typical results for the monthly data of January, April, July, October and all the yearly data (1860–1985). Level of significance 95%

Precipitation amount cycles (yr)							Precipit. intensity cycles (yr)				
J	2.3	4.5		12.2	34.1		2.4	4.4	9.1		33.3
A	3.2			9.2	33.1		2.4	4.3	9.0	17.1	32.2
J	2.2			9.3	23.8	44.8	2.3	6.3			32.5
O	3.1		6.2		23.8		3.2	6.4		24.8	
Annual	3.1		8.7		23.8		3.2		8.8		

Consequently, it can be concluded that despite the fact that the periods detected are of low significance, they show similarities to those reported by other workers suggesting they may, indeed, be real (and possibly explicable in terms of solar effects, etc.). There also were found periodicities (e.g. 4.5, 6.3, and 8.0 or 9.0 yr) which are not clearly related to any astrophysical phenomenon.

6. Some Concluding Remarks

A long period precipitation record for (MINOA) Athens was examined to look for characteristics, trends, and periodicities that could be extrapolated into the future. Analysis of the data indicates that although trends in single station rainfall are often unreliable our results do suggest a certain stability in the rainfall patterns of SE Europe during the last century. The detailed analysis allows the following brief conclusions:

(i) The precipitation series is one of the longest in south-east Europe and has been recorded without interruption since 1858. The original data were checked and are archived in MINOA.

(ii) The station changed sites nine times from 1858 to 1890, but the station has practically not changed since 1890 to date. Homogeneity tests show that quality of the data is found to be good from 1890 to 1985.

(iii) The characteristics and the types of the rain-gauges are known; the observers and their operational procedures are also known.

Some problems may arise concerning the representativeness of the site in the recent years because of the rapid growth of the city. However, the long-time-series of the data and their quality makes their analysis quite interesting.

(iv) The seasonal distribution of the precipitation is simple with the maximum in late autumn and early winter and the minimum in summer. The seasonal series are homogeneous throughout the recent 90 yr. Persistence and repeatability of the meteorological conditions influencing precipitation are not all significant.

(v) The precipitation pattern is typical of the Mediterranean climate. This pattern is closely related to large-scale systems rather than to local effects.

(vi) It rains only 4% of the time. There is one maximum and one minimum of intensity during the day and a decreasing trend of precipitation intensity.

(vii) The annual amounts and the annual number of precipitation days are variable. Fairly wide variations occur in monthly values.

(viii) There is no significant trend in the annual rainfall data. The trend analysis gives a 65 yr wave for the number of precipitation days. This wave has no statistical significance and thus cannot allow predictions. The precipitation amount shows a different trend, giving a 60 yr wave, which is not in phase with the number of precipitation days. It is very hard to extrapolate conclusions on the general climatic context. However, the analysis indicated the stable aspect of the precipitation climate of Athens.

(ix) There exist some periodicities. Periods of 2.3, 9.0 to 12.0 and 23.8 yr are frequently occurring and could probably be related to the general circulation index and to the solar cycles. There exist also unexplained cycles (except for the seasonal cycle).

(x) Precipitation in towns is one of the most complex problems of analysis in the whole field of urban climatology. The main difficulty is to separate the purely urban controls from the much stronger influences of synoptic climatology and topography within the built-up area. Reliable predictions of the potential impact of human activities on climate will only be made when a better understanding of the mechanisms of climatic change is achieved in addition to the development of climate models.

The above results can be regarded as partially conclusive until comparisons will be done with long-time precipitation series existing in other south European cities.

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Appendix: Complete Table of Original Monthly and Annual Precipitation Amounts (mm) at MINOA (1858–1985)

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1858	36.0	40.0	30.0	2.0	7.5	17.0	27.0	25.0	16.0	25.0	41.0	26.0	202.5
1859	32.3	56.6	18.5	–	–	–	–	6.8	2.3	5.4	75.1	72.4	–
1860	37.7	90.9	41.5	14.7	11.7	10.1	17.8	0.0	2.0	25.3	67.9	64.5	384.1
1861	14.4	1.3	34.8	10.7	76.0	21.0	1.7	9.9	1.7	52.8	3.5	90.5	318.3
1862	43.9	16.6	10.0	3.2	6.1	43.6	2.6	0.0	6.6	0.0	102.9	9.1	244.6
1863	27.3	2.6	74.0	8.6	1.8	13.9	0.0	0.1	5.4	6.0	68.7	74.4	282.8
1864	75.6	74.9	13.7	11.8	57.0	11.2	0.0	0.0	52.7	140.8	241.0	41.5	720.2
1865	45.3	110.3	44.3	10.7	0.6	0.7	51.2	4.2	5.6	35.5	50.7	13.0	372.1
1866	21.7	24.9	23.3	1.9	19.7	3.2	0.0	0.0	31.8	22.6	135.6	79.6	364.3
1867	31.1	2.6	24.1	17.6	3.5	22.1	3.6	0.8	0.5	74.0	54.8	101.9	336.6
1868	72.5	8.2	78.7	16.3	29.5	3.9	1.5	0.2	6.1	69.7	113.3	24.0	423.9
1869	48.5	16.6	69.3	44.7	28.5	12.3	2.7	19.4	28.7	13.6	29.0	66.3	379.6
1870	59.1	32.0	51.6	64.2	6.3	0.1	0.0	29.3	30.7	28.8	25.0	80.7	407.8
1871	110.8	27.5	26.2	21.6	19.9	3.1	0.0	0.1	7.5	183.7	111.3	67.3	579.0
1872	124.9	15.4	9.1	18.0	1.7	42.4	1.1	6.6	0.0	26.0	113.8	79.2	438.2
1873	5.7	37.7	51.1	17.2	77.8	6.1	1.7	4.3	17.7	49.9	28.7	42.4	340.3
1874	51.6	32.5	32.4	19.4	50.2	0.0	0.0	0.1	4.7	64.7	74.1	102.5	432.2
1875	34.0	97.7	75.0	31.5	48.3	8.0	4.8	0.0	56.1	42.3	70.0	51.1	518.8
1876	2.4	7.5	7.5	11.6	15.0	6.3	11.1	9.2	0.0	35.8	95.2	12.3	213.9
1877	11.7	27.5	37.5	7.0	32.9	19.7	4.6	33.6	13.8	163.6	87.5	48.6	488.0
1878	38.3	34.4	33.6	10.2	6.5	7.5	13.8	4.4	19.5	1.7	63.1	123.0	356.0
1879	139.8	29.8	28.3	24.1	8.5	0.0	0.0	0.0	15.7	63.0	60.6	46.9	416.7
1880	30.2	25.3	33.1	27.6	11.7	8.9	1.2	62.9	39.6	16.8	27.7	35.8	320.8
1881	90.8	93.5	41.1	3.7	17.8	0.2	35.2	0.0	8.6	7.4	19.6	197.0	514.9
1882	76.0	28.4	66.5	34.8	15.4	4.6	4.6	48.2	0.0	14.0	14.4	63.8	370.7
1883	93.7	52.1	85.7	61.2	26.3	11.3	1.8	53.5	3.5	210.8	115.4	131.1	846.4
1884	60.7	15.8	17.0	28.0	21.7	8.2	15.4	37.4	2.9	4.7	96.2	51.6	359.6
1885	112.3	66.5	86.3	15.4	6.9	28.5	47.9	0.0	3.1	46.2	254.2	50.7	718.0
1886	165.9	77.7	61.9	39.5	33.7	3.7	6.8	23.2	0.0	10.9	34.6	64.1	522.0
1887	24.8	17.9	6.5	53.7	0.0	15.0	0.0	0.5	13.3	58.3	131.3	44.5	365.8
1888	33.4	42.4	14.9	10.1	60.6	0.0	0.0	9.2	15.2	43.6	50.4	22.6	302.4
1889	80.3	39.1	65.0	4.2	22.9	49.0	29.7	0.3	5.3	21.6	10.3	57.8	385.5

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1890	4.5	45.8	18.2	23.6	12.7	8.7	0.0	0.0	22.4	27.0	90.8	102.7	356.4
1891	55.3	16.9	10.3	19.5	1.0	0.0	7.8	0.0	2.1	24.6	26.9	41.7	206.2
1892	32.5	44.3	22.3	33.0	11.6	15.6	0.3	0.0	6.6	4.3	43.6	34.4	248.5
1893	86.0	32.8	26.3	33.4	9.2	1.7	0.0	3.9	11.6	21.6	43.2	147.2	416.9
1894	75.5	5.1	7.1	47.2	8.1	0.5	0.7	0.0	8.0	33.1	74.1	96.2	355.6
1895	35.8	78.2	54.9	12.9	9.2	5.2	15.9	0.0	4.9	35.4	16.3	68.8	337.5
1896	65.0	13.6	4.7	35.1	4.5	1.6	4.7	0.0	57.1	13.0	172.9	52.3	424.5
1897	64.7	6.1	9.9	9.9	23.0	101.7	1.7	15.6	23.5	79.3	8.0	36.3	379.7
1898	7.3	23.8	23.6	2.0	10.7	0.5	0.0	0.0	0.0	24.7	1.5	21.6	115.7
1899	47.4	22.4	8.2	29.8	7.9	5.7	7.1	2.8	26.2	27.1	200.8	30.4	415.8
1900	70.4	58.1	23.6	22.7	20.9	44.1	2.3	0.0	0.0	8.3	37.9	71.1	359.4
1901	30.2	49.1	7.5	11.8	20.2	119.6	1.9	13.1	15.0	46.0	86.7	34.8	435.9
1902	14.9	29.7	39.5	1.2	8.1	2.2	0.0	5.8	0.1	101.0	50.2	44.2	296.9
1903	4.9	43.5	41.1	13.2	21.5	9.1	10.3	0.0	0.0	10.7	26.3	138.1	318.7
1904	127.7	22.8	16.5	12.7	34.5	8.0	0.4	0.0	16.5	61.1	45.8	57.5	403.5
1905	116.9	55.0	84.3	2.9	2.9	11.6	2.4	0.0	0.0	90.7	26.4	11.1	404.2
1906	32.7	28.3	24.7	56.6	75.7	19.2	51.1	35.3	2.5	50.0	56.4	54.7	487.2
1907	39.6	61.0	31.9	31.6	0.0	5.9	0.0	55.1	0.3	0.0	33.1	48.1	306.6
1908	41.3	17.5	37.3	4.7	24.1	2.6	1.2	0.0	70.5	22.0	62.1	137.2	420.5
1909	58.5	37.8	23.9	24.4	11.0	16.9	0.0	5.0	45.5	18.5	69.9	35.1	346.5
1910	146.6	106.8	59.3	16.9	33.6	23.0	0.0	1.8	7.7	0.8	57.1	148.3	601.9
1911	20.9	17.0	44.5	50.6	19.5	5.0	0.4	10.4	18.3	15.4	107.1	84.5	393.6
1912	39.3	67.2	21.7	18.9	16.3	8.3	13.4	0.0	0.9	16.7	206.9	94.7	504.3
1913	15.1	68.1	15.2	1.4	22.0	0.2	0.0	74.3	66.2	45.7	27.3	52.3	387.8
1914	111.8	47.8	7.4	27.8	16.9	15.7	13.4	8.6	8.5	36.6	111.0	48.4	453.9
1915	41.1	44.1	22.3	68.3	12.1	0.0	5.0	0.7	29.3	29.6	20.2	4.1	276.8
1916	28.8	46.2	28.4	18.4	26.0	0.5	4.1	0.0	4.3	18.6	46.9	95.4	317.6
1917	84.0	55.9	10.8	45.9	26.4	19.2	0.0	0.0	0.0	63.0	91.0	142.1	538.3
1918	5.9	38.2	81.4	7.5	7.7	9.0	0.8	2.5	0.0	118.1	110.3	87.6	469.0
1919	99.0	25.5	34.3	7.7	24.3	16.1	0.0	12.2	5.6	67.0	33.1	45.0	369.8
1920	41.2	50.6	20.1	31.5	60.8	5.2	13.9	6.2	0.0	41.6	53.9	110.2	435.2
1921	27.0	32.8	10.3	29.4	45.6	51.6	0.2	0.0	64.8	85.4	107.2	70.1	524.4
1922	46.5	43.8	4.9	3.2	53.8	1.2	0.0	0.0	0.6	12.2	71.9	48.6	286.7
1923	102.0	26.3	28.2	16.7	30.0	40.3	0.4	2.9	0.0	7.8	26.0	70.6	351.2

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1924	58.8	40.4	32.7	0.0	20.2	22.6	0.0	12.8	33.5	62.2	54.0	30.7	367.9
1925	4.9	69.9	101.6	7.3	35.6	16.2	0.8	0.0	0.0	34.4	137.1	6.1	413.9
1926	57.0	31.2	2.1	1.3	3.7	0.4	0.3	3.0	0.0	0.0	38.6	151.6	289.2
1927	30.3	40.7	46.5	24.3	2.0	0.0	10.4	1.2	9.6	92.0	0.3	72.0	329.3
1928	104.0	29.0	76.4	7.2	2.8	0.0	0.0	2.8	0.1	5.1	104.6	112.7	444.7
1929	55.8	35.0	17.1	8.3	9.6	0.0	0.0	10.1	59.2	69.0	39.5	68.3	371.9
1930	40.8	127.6	12.3	29.4	33.7	14.9	7.3	0.9	38.1	97.3	16.7	71.6	490.6
1931	115.3	51.9	29.3	54.5	36.8	24.3	0.0	2.1	9.8	10.8	20.3	165.9	521.0
1932	29.5	22.3	91.2	12.1	1.0	3.3	0.0	1.7	0.0	4.9	70.8	22.8	259.6
1933	68.9	42.2	11.4	29.8	27.3	23.8	29.9	1.9	10.2	36.8	27.9	104.6	414.7
1934	53.4	103.9	45.2	4.3	17.4	13.8	4.4	0.0	4.2	9.7	56.0	97.2	409.5
1935	85.0	37.8	36.9	1.4	2.4	5.5	0.0	0.0	20.0	30.2	28.0	86.8	334.0
1936	70.5	58.9	31.5	6.3	47.7	73.2	1.1	11.4	1.6	89.4	114.0	68.8	574.4
1937	8.7	36.1	12.9	11.6	97.0	1.3	17.0	1.3	13.9	117.5	88.0	105.8	511.1
1938	34.9	57.4	32.2	47.6	3.7	0.0	10.3	9.3	29.3	77.6	53.9	119.0	475.2
1939	68.4	38.3	116.6	16.9	1.7	34.3	0.0	7.8	17.9	33.0	80.4	105.4	520.7
1940	95.7	27.3	23.6	20.4	33.3	1.8	12.7	3.4	0.0	26.4	63.9	42.5	351.0
1941	31.3	55.1	7.1	9.1	9.5	8.6	0.0	0.4	0.9	74.4	19.8	73.3	289.5
1942	138.3	62.7	35.6	22.2	0.4	13.3	1.2	27.4	0.0	56.2	45.8	19.8	422.9
1943	46.9	13.4	52.7	13.3	16.1	18.4	0.0	0.0	21.7	9.4	22.9	38.5	253.3
1944	40.5	84.5	24.4	61.9	0.3	0.6	9.6	69.4	0.8	41.0	9.3	91.6	433.9
1945	81.8	10.1	24.4	22.3	0.0	0.1	0.0	0.5	2.8	32.6	136.8	110.7	422.1
1946	44.2	15.8	74.6	26.0	24.6	0.4	3.2	0.0	0.0	42.1	12.9	124.1	367.9
1947	76.5	13.2	2.3	0.8	0.9	48.8	6.0	1.1	0.0	49.6	52.0	51.9	303.1
1948	41.5	57.4	14.8	24.7	44.3	23.7	0.0	0.0	13.9	0.5	36.7	23.0	280.5
1949	67.0	17.0	33.3	9.2	0.0	38.9	39.5	0.9	144.4	68.6	52.1	15.0	485.9
1950	22.5	11.5	86.5	24.3	23.7	0.4	0.0	0.0	35.7	9.2	12.7	129.4	355.9
1951	117.4	21.8	27.9	7.9	22.6	34.6	2.7	38.2	18.1	35.2	68.5	49.8	444.7
1952	39.3	51.3	73.9	0.2	34.7	3.7	1.4	0.0	2.7	33.4	86.5	117.8	444.9
1953	83.3	7.0	36.2	30.6	100.3	7.2	0.9	3.2	2.0	126.2	15.6	49.0	461.5
1954	72.2	60.8	24.8	53.8	40.9	1.1	0.0	0.0	9.3	94.3	77.4	55.1	489.7
1955	74.8	43.9	11.0	58.8	0.1	0.6	7.0	10.9	21.7	260.9	112.9	9.4	612.0
1956	30.8	56.5	71.2	20.0	3.8	2.4	0.0	0.0	5.4	10.5	57.0	52.1	309.7
1957	43.7	9.5	10.6	17.4	47.2	2.4	0.0	0.0	4.8	112.4	46.8	37.0	331.8

Year	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1958	91.5	7.5	36.1	30.1	17.1	12.2	0.0	0.0	49.4	8.4	89.2	5.4	346.9
1959	23.4	0.9	25.2	28.0	16.2	3.1	24.1	0.2	9.1	27.0	32.4	38.5	228.1
1960	71.7	19.6	22.8	24.4	4.4	6.6	0.0	18.5	9.3	12.7	81.9	131.6	403.5
1961	93.5	27.6	77.2	6.8	7.3	1.1	0.0	0.0	0.0	14.3	85.5	44.0	357.3
1962	44.8	43.4	10.6	20.5	6.9	1.8	0.5	0.0	78.7	42.8	89.5	138.7	478.2
1963	66.7	21.4	17.3	10.1	86.3	0.9	9.8	0.2	0.0	143.7	47.1	55.7	459.2
1964	73.4	36.6	18.8	10.8	3.4	32.3	0.0	0.0	12.4	17.9	17.5	50.0	273.1
1965	72.4	136.6	61.6	24.6	17.0	4.2	0.0	2.8	0.0	3.7	23.7	32.4	379.0
1966	37.0	13.6	60.6	25.7	22.5	10.5	0.0	0.9	38.0	51.1	31.1	92.6	383.6
1967	24.9	43.2	15.1	23.9	26.1	4.8	12.7	0.0	25.9	112.0	56.7	61.5	406.8
1968	80.9	52.8	30.7	9.8	48.7	60.0	0.0	3.6	0.2	69.2	91.5	98.4	545.8
1969	54.5	12.6	57.7	16.0	3.2	0.6	0.0	0.0	15.0	0.1	18.3	122.9	300.9
1970	30.1	47.0	26.3	0.9	15.9	3.8	1.5	0.0	14.9	28.1	14.0	57.9	240.4
1971	66.2	67.8	74.3	12.7	2.2	0.0	1.4	1.4	9.6	20.1	24.9	79.6	360.2
1972	70.0	62.9	12.9	91.9	10.5	0.0	12.0	23.1	7.3	148.8	0.1	11.4	450.9
1973	68.9	68.8	74.3	9.8	4.3	0.6	30.4	0.6	44.4	16.2	27.5	52.3	398.1
1974	38.1	78.2	67.3	16.0	32.8	25.1	0.0	3.6	12.6	19.5	38.0	30.7	361.9
1975	28.8	43.4	29.7	17.3	49.2	8.4	6.8	29.6	0.0	22.5	73.0	144.2	452.9
1976	38.8	117.8	30.1	38.4	15.7	2.6	0.1	17.2	13.5	130.4	72.0	21.6	498.2
1977	10.7	11.0	10.0	21.3	1.2	9.8	0.0	0.0	20.4	5.8	153.9	109.6	353.7
1978	58.6	57.7	21.0	32.9	9.6	2.3	0.0	0.0	47.3	88.9	33.9	92.3	444.5
1979	21.3	49.8	14.3	0.7	56.3	0.0	1.6	0.5	1.1	101.7	78.5	36.3	362.1
1980	33.0	12.8	86.0	34.0	12.1	23.7	0.0	2.1	0.6	101.7	29.2	76.7	411.9
1981	85.6	30.9	24.0	36.7	2.5	0.0	1.9	0.4	0.0	23.1	31.9	86.5	323.5
1982	29.4	56.7	51.7	53.2	26.6	0.3	9.8	1.2	0.1	17.9	65.3	86.7	398.9
1983	1.9	77.4	44.3	12.3	24.8	1.4	5.2	14.6	2.5	22.3	73.0	76.6	356.3
1984	39.9	34.3	85.4	116.3	1.4	0.0	23.0	9.8	0	0.7	19.9	50.1	380.8
1985	75.4	27.2	84.9	32.0	9.1	0.4	5.9	0.0	1.3	24.2	29.3	39.4	329.1