Tellus (1979), **31**, 413–420

Temporal fluctuations of seasonal precipitation in Jerusalem

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(Manuscript received August 14, 1978; in final form May 2, 1979)

ABSTRACT

The annual rainfall in Jerusalem during the period 1846–47 to 1953–54 is studied by the method of time spectrum analysis and filtering techniques. The effect of different methods of spectral presentations is then demonstrated. A prominent significant peak appears in the spectrum at a period of 3.0–3.3 years and a secondary peak is evident at 2.15 years. More than 55% of the total variance of annual rainfall in Jerusalem is concentrated in the period band between 2 and 4.3 years. The above two peaks were compared with published spectra of rainfall and other meteorological parameters in other parts of the world and found compatible with the Southern Oscillation (S.O.) and the Quasi Biennial Oscillation (Q.B.O.), respectively. When the data were subdivided into two equal subperiods, the 3.0–3.3 years' peak remained the dominant feature in both spectra, whereas the 2.15 years' peak disappeared altogether in the second subperiod. The implications of this behaviour are discussed.

1. Introduction

Interest in climatic fluctuations has been revived recently. A considerable effort is focused on an attempt to understand fluctuations in aridity of certain regions located in the vicinity of large deserts (e.g. the Sahel). A theory has been developed (Otterman, 1974; Charney, 1975) which attempts to relate fluctuations in rainfall in the Sahel and possibly other regions with fluctuations of the surface albedo caused by the activity of man (e.g., over-grazing by cattle). While this theory is quite attractive it may be asked whether this process which is locally instigated by the activity of man is the major mechanism causing rainfall fluctuations in the vicinity of large deserts. Another possibility advocated by researchers is that these variations result from fluctuations inherent in the general circulation of the atmosphere and are global in nature and thus could be detected in other parts of the world.

The Eastern Mediterranean is located on the northern flanks of the vast Sahara–Arabian deserts. It is assumed that fluctuations in annual rainfall in the Eastern Mediterranean are related to fluctuations in the position of the northern boundary of the desert. Variations of the position of this boundary are presumably instigated by variations in some characteristics of the westerlies (e.g. intensity of the westerlies and/or blocking activity, etc.) which in turn are closely related to the intensity of the Hadley cell and its associated convection over the equatorial region (Bjerknes, 1969). Thus, an analysis of the secular variations of rainfall in the Eastern Mediterranean can offer some clues as to the causes of secular variations in the northern boundary of the Sahara Desert near that region.

A time series of annual rainfall data of the old city of Jerusalem consisting of 108 years has been reconstructed by Rosenan (1955). This unique data set offers an excellent opportunity to study secular variations of the northern boundary of the Sahara–Arabian desert in the Eastern Mediterranean. A statistical analysis of this time series has been published by Neumann (1956). He used the time series mainly to establish probability distributions of certain annual rainfall amounts. Another statistical investigation (Gabriel and Kesten, 1963) using roughly the same data period was concerned,

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among others, with periodic variations and serial dependence in the data. They concluded that the amount of rainfall in successive years may be regarded as independent and that no significant cycles are present in the data.

The first purpose of the present paper is to re-examine these results using the spectrum analysis technique. Spectrum analysis has been used in several papers to study secular variations in rainfall. Granger (1977) in a study of rainfall in California reported a significant peak in the rainfall spectra at a period of nearly 2.15 years and suggested its association with the Quasi Biennial Oscillation (Q.B.O.). The Q.B.O. has been observed clearly in many temperature records as well (e.g. Landsberg et al. 1959). Granger also found a peak in the vicinity of 5–6 years and related it to interannual variations in the activity of the North Pacific High.

Rodhe and Virji (1976) analysed rainfall data from East Africa and found major periodicities at periods of 5.0 to 5.7, 3.3 to 3.6 and 2.1 to 2.2 years. They point out the possible association of the first two peaks with the Southern Oscillation (S.O.) and that of the last peak with the Q.B.O.

The second purpose of the present paper is to compare the spectra and some other features of the Jerusalem rainfall with (1) California rainfall; this is because the state of California lies on the same latitude as Jerusalem and has a Mediterranean climate characterized by rainy winters and dry summers. And with (2) East African rainfall; this is because East Africa lies in the same longitude as Jerusalem and thus variations in the intensity of the Hadley circulation and the I.T.C.Z. at that longitude could be associated with variations in some features of the westerlies controlling the rainfall during the cold season in the Eastern Mediterranean. It is hoped that this study will contribute to an improved understanding of the secular and spatial variations of global phenomena such as the Q.B.O. and the S.O. and their association with local climatic variations, especially in the transition zones between deserts and humid climates.

2. Data and method of analysis

The data used for the study consist of a unique time series of annual rainfall amounts in the old city of Jerusalem (at the English Mission Hospital) reconstructed by the late Rosenan (1955). The period of observation starts in the rain season of 1846–47 and ends in the rain season of 1953–54. Two rain seasons, 1849–50 and 1859–60 are missing and are linearly interpolated so that the total number of data used is 108. Time spectrum analysis utilizing the lag correlation method (Blackman and Tukey, 1959; Munk et al., 1959) is performed on the 108 annual rainfall data in Jerusalem. Spectrum analysis is widely used in the analysis of meteorological data. Howerer, care must be taken in the interpretation of spectra (e.g. Chiu, 1967). The purpose of using spectrum analysis in the present paper is to detect distinct periodicities in the annual rainfall in Jerusalem and try to relate them to periodicities in rainfall and other meteorological variables in other parts of the world.

The detection of periodicities from results of spectrum analysis is by no means trivial. Numerous methods of presentation and interpretation of the spectrum are being used in the literature, but there is still no *standard* method widely used. The logarithmic spectrum (namely, the power density per unit natural logarithm of frequency plotted against the natural logarithm of frequency) is utilized in many studies. This spectrum is obtained from the ordinary spectrum by the transformation;

$$\int_{\nu_1}^{\nu_2} P(\nu)\, d\nu = \int_{\ln \nu_1}^{\ln \nu_2} \nu P(\nu)\, d(\ln \nu) \qquad (1)$$

where ν is the frequency, $P(\nu)$ is the power density per unit frequency. This presentation of the spectrum is superior to other spectral presentations (as far as dominant scales are concerned) since it can be shown (Zangvil, 1977) that if a sine wave of finite length is spectrally analysed the peak of the logarithmic spectrum is located exactly at the frequency of the wave. On the other hand, in other presentations the peak occurs off the exact frequency of the wave. For semi-periodic functions the discrepancy can be quite large, thus determination of periodicities may be meaningless with the use of other methods of presentation. A natural outcome of the choice of the logarithmic presentation is the null hypothesis of "no dominant scale". This continuum is represented by a horizontal line on the logarithmic presentation. The line is drawn in such a way that the area under it equals the total variance under consideration. This line resembles, to a certain extent, a first-order Markov process with a persistence between about 0.5 to 0.7.

In the next section the statistical significance of spectral peaks is determined by applying the chi-square test to the spectra in two ways. First, the spectra are plotted on a conventional linear frequency scale and compared to the white noise null continuum. Then the spectra are transformed to a logarithmic scale by using the transformation (1) and compared to the "no dominant scale" null continuum.

3. Results

Before presenting the results of the spectrum analysis some basic statistics of the time series are given in Table 1.

3.1. *Short period variations*

Spectrum analysis is performed on the series of annual rainfall data using the lag correlation method. A lag of 15 years is used and 16 spectral estimates of power density $P(\nu)$ are obtained. The number of degrees of freedom is 13.9. Fig. 1(a) shows the power spectral density $P(\nu)$ (per unit frequency) plotted against the frequency. There is a distinct peak at a period of 3.3 years and two secondary peaks at 6.0 and 2.15 years. None of these peaks is significant at the 95% level when we use a white noise null hypothesis. When the spectrum is transformed according to eq. (1) and $\nu P(\nu)$ is plotted against $\ln \nu$ (Fig. 1(b)), the main peak is located between 3.3 and 3.0 years. There is also a secondary peak at 2.15 years but the peak at 6.0 years flattened out and appears faintly at 6.0 years. Two features of this spectrum stand out: First, the prominent peak at 3.0–3.3 years and second, the small amount of variance at long periods longer, say, than 7 years.

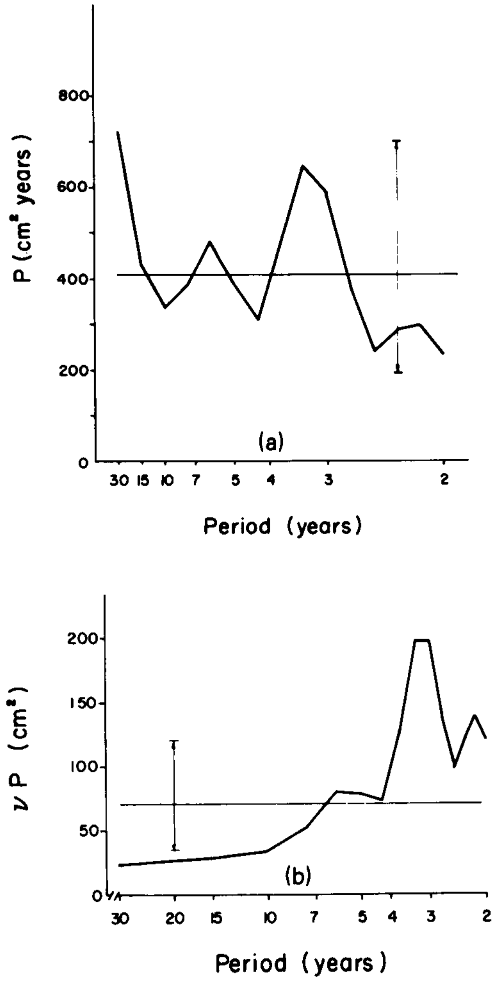

Fig. 1. Power spectrum of annual rainfall amounts in the old city of Jerusalem for the period 1846–47 to 1953–54. (a) Power density per unit frequency ν plotted against ν The horizontal line is the white noise null hypothesis and the arrows mark the 5% and 95% confidence limits. (b) Power density per unit $\ln \nu$ plotted against $\ln \nu$. The horizontal line is the "no-dominant scale" null hypothesis and the arrows mark the 5% and 95% confidence limits.

Table 1. *Some basic statistics of the Jerusalem annual rainfall data*

Average, $\bar{x}$	Lowest amount (in 1922–23)	Percent of average, $x_{min}/\bar{x}$. 100%	Highest amount (in 1877–78). x_{max}	Percent of average $x_{max}/\bar{x}$. 100%	Standard deviation, σ	Percent of variation, $\sigma/x \cdot 100\%$	Coefficient of skewness
55.99 cm	24.9 cm	44.5%	109.0 cm	194.7%	14.96 cm	26.7%	~0.3

The significance test shows a very high significance of the 3.3–3.0 years peak, but the 2.15 years' peak is also significant at the 95% level. The fact that peaks become significant when the spectrum is plotted on the logarithmic scale resulted essentially from the use of the "no dominant scale" null hypothesis as compared to the white noise hypothesis used in Fig. 1(a).

The finding of statistically significant peaks in Jerusalem rainfall has not been reported in the literature. A statistical analysis of the series of annual rainfall in Jerusalem covering roughly the same period (1860–61 to 1959–60) has been made by Gabriel and Kesten (1963). They reported no significant long or short period cycles in the data. Their conclusion was based on a statistical analysis similar to that performed in the first part of this section. They also examined the serial correlation (lag 1) and found it to have the value $\rho = 0.11$ which they claimed to be statistically insignificant. This value can be explained as being due to short period variations.[1]

Granger (1977) made a comprehensive spectral analysis of annual rainfall data of numerous stations in California but no significant peak has been found near 3 years.

However, if one transforms Granger's spectra by multiplying it by the frequency ν to obtain the power per unit $\ln \nu$, it can be easily verified that several stations have peaks near 3 years (e.g. Los Angeles, at 2.9 years; San Luis Obispo at 3.0 years, and Eureka at 3.5 years). A weaker peak can be found at several stations at nearly 5 years.

It is possible that a mechanism similar to that causing the rainfall oscillation with a peak of 3.0–3.3 years in Jerusalem is also responsible for the peak near 3 years in California. The other peak in the Jerusalem spectra found at 6.0 years on the conventional presentation and same period on the logarithmic presentation is statistically insignificant with both methods of evaluating the statistical significance. Still, it is of interest to note a corresponding peak of 5.0 years reported by Granger. He associates this variation in rainfall with variations in sea surface temperature over the Pacific Ocean reported by Namias (1969) and with pressure fluctuations over the Pacific with a period of about 5 years (Wanger, 1971; White and Clark, 1975). There is a possibility that processes over the Pacific also affect the Eastern Mediterranean region through atmospheric teleconnections. This may possibly explain the peak in the Jerusalem spectrum at 5–6 years. On the other hand, it is more likely that the prominent peak at 3.0–3.3 years is associated with interannual variations of blocking activity over the Atlantic which is known to strongly affect the synoptic systems bringing rain to the Eastern Mediterranean. However, no literature concerning the interannual variations in blocking activity over the Atlantic has come to the author's attention.

Rodhe and Virji (1976) reported prominent spectral peaks at periods of 2.1–2.2 years 3.3–3.6 years and 5–5.7 years in East African rainfall. Their spectra were presented on a conventional linear frequency scale. If it is transformed to a logarithmic scale the peak near 3.5 years shifts to 3.3 years and becomes the most prominent peak in the spectra of most of the East African stations. It is not inconceivable that the connection that Rodhe and Virji are alluding to between East African rainfall oscillations and the Southern Oscillation (Troup, 1965) is present also in the fluctuations of rainfall in Jerusalem. The connection between East African rainfall and the rainfall in Jerusalem may be the following: more than average rainfall in East Africa during the main rain period of January to April is probably associated with a more intense Hadley circulation This circulation is causing strong westerlies or high index in the same longitude resulting in reduced rainfall in the Eastern Mediterranean. Lower than average rainfall in East Africa may be associated with a weak Hadley cell giving rise to frequent blocking activity over the Atlantic Ocean (compare to White and Clark, 1975).

Angell and Korshover (1977) report a global temperature oscillation with a period 3.25 years in three regions in the troposphere. The oscillation shows up in the equatorial region and in the subtropics between 10° N and 30° N since 1965. The authors point out the compatibility of the period of oscillation and the Southern Oscillation.

The foregoing discussion suggests the existence of some connection between the Southern Oscillation and the rainfall in Jerusalem. The Southern Oscillation has been recognized in recent literature to be a world wide phenomenon having a dominan

[1] If an artificial sinusoidal time series is generated having a period of 3 years, the lag 1 correlation is $\rho = 0.22$.

period of 3 to 6 years (Trenberth, 1976). The rain periodicity of 3.0–3.3 years and the secondary one at 5 years found in Jerusalem are in accordance with that.

3.2 *Comparison of the spectra for two equal sub-periods*

An attempt to determine to what extent the features found above are stationary in time is made next. This is done by subdividing the 108 years' period into two equal subperiods and performing the spectrum analysis on these subperiods separately. By doing so the number of degrees of freedom is roughly halved. Results are shown in Figs. 2 and 3.

Fig. 2(a) shows the spectrum of the first 54 rain seasons plotted on a linear frequency scale. The prominent peak is the one at 3.3 years. The second peak which appeared in the spectrum for the 108 years, at 6.0 years is much more prominent in this spectrum and the same is true for the peak at 2.15 years. Another difference between the two spectra is that the low at 10 years is more pronounced in the first sub-period and in addition the spectral estimates at 15 and 30 years are also considerably lower in this sub-period. Application of the standard procedure to determine the statistical significance of these features shows that none of the peaks is significant at the 95% level. The two lows, nevertheless, are marginally significant. When the

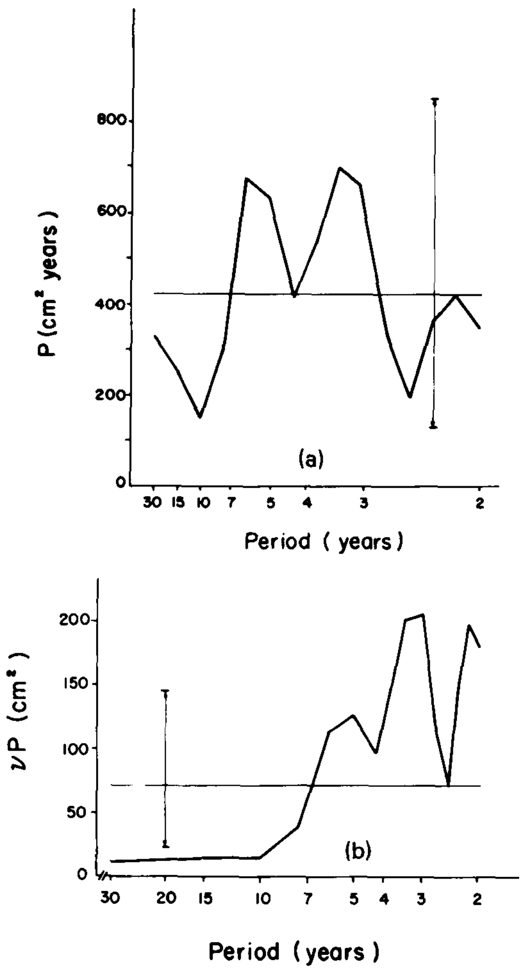

Fig. 2. Same as Fig. 1 but for the sub-period 1846–47 to 1899–1900.

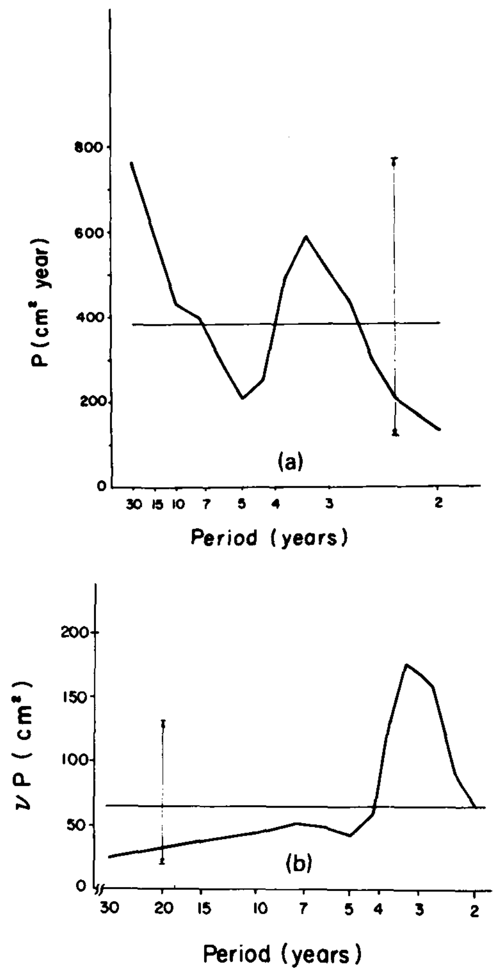

Fig. 3. Same as Fig. 1 but for the sub-period 1900–01 to 1953–54.

spectrum of this sub-period is plotted on a logarithmic scale (Fig. 2(b)) three major peaks are evident: at 3.0, 2.15 and 5.0 years. The first and last peaks slightly changed their location from that in Fig. 2(a).

The significance test shows the peak at 5.0 years to be insignificant. However, the peaks at 3.0 and 2.15 years are clearly significant at the 95% level. Another interesting feature is the low level of power beyond say, 10 years, which is significant at the 95% level.

In the second sub-period several outstanding features are evident (Fig. 3). First the obvious persistence of the peak at 3.3 years, second the disappearance of the peak at 2.15 years and third the relatively high level of power density at long periods. Again, none of these features is found to be statistically significant. However, when this spectrum is plotted on the logarithmic scale and the significance test is performed using the "no dominant scale" null hypothesis, the peak at 3.3 years is significant at the 95% level. It should be remarked that the second subperiod is characterized generally by below-average rainfall.

3.3 *Long period variations*

Fig. 4 shows a 10-year running mean of the time series and the series filtred with a 5-point filter. The most pronounced features of this running mean are the above-average rainfall from about 1868 to 1911 with a peak around 1892–93. The 10-year running mean exceeded 69.0 cm or 123% of the long-term mean. The other outstanding feature is the below-average rainfall between about 1912 to 1937 with the lowest 10-year running mean of 41.2 cm or 77%. At this point it is not possible to make an assumption or even speculate on the cause of these very large long-term fluctuations. However, it is interesting to note the existence of a general similarity between the 10-year running mean of Jerusalem rainfall and the 20-year running mean of several California stations, shown in Fig. 3 in Granger's (1977) paper. Also the Jerusalem data filtered with a 5-point filter contain many features common with the 5-year running means of annual rainfall in California, shown in the same figure. These variations are almost in phase in both regions. This suggests that variations in precipitation with a period of over 5 years originate in both California and the Eastern Mediterranean in the same global climatic controls. However, more work is needed to determine these connections.

The long-term variations in the general circulation may also affect the intensity and regularity of the Q.B.O. As suggested by the disappearance of the 2.15 years' peak from the spectrum of the second sub-period, the second sub-period is characterized by lower than average rainfall. If lower rainfall in Jerusalem on a scale of several decades is associated with strong westerlies (e.g. Winstanley, 1973), the disappearance of the Q.B.O. may be explained by the lack of blocking activity and its associated stationary, vertically propagating ultra-long waves.

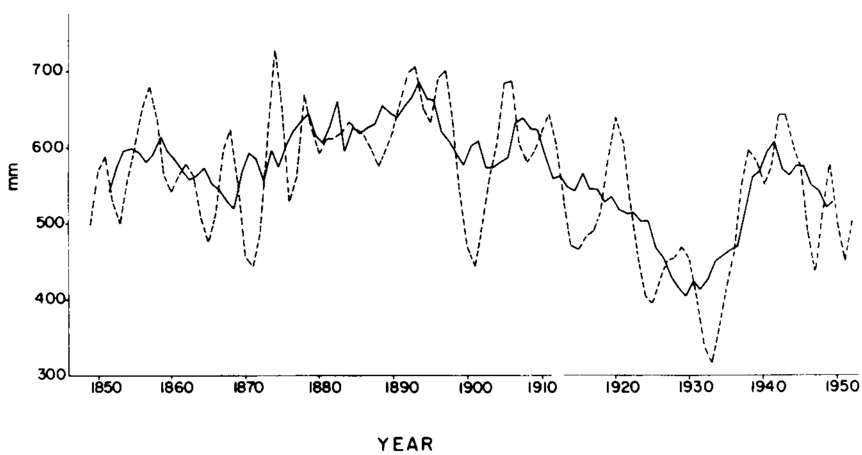

Fig. 4. Jerusalem annual rainfall data smoothed with a 10-year running mean (solid line) and with a 5-point filter with weights 0.05; 0.25; 0.40; 0.25; 0.05 (dotted line).

4. Summary and conclusions

A series of 108 annual rainfall data of the old city of Jerusalem has been examined to detect possible short- and long-term fluctuations and periodicities. The method of spectrum analysis has been employed the most. The most prominent feature of the spectrum is a peak at a period of 3.0 to 3.3 years. Secondary peaks exist near 2.15 and 6.0 years. The peak at 3.0 to 3.3 years and probably also the weak peak at 6 years may be associated with the now widely recognized global oscillation called the Southern Oscillation (S.O.). The peak at 2.15 years is probably associated with the Quasi Biennial Oscillation (Q.B.O.).

The peak at 3.0–3.3 years remains the dominant feature of the spectrum even when the total period of 108 years has been subdivided into two equal sub-periods. The peak remained at the same period and its intensity did not change considerably. This fact supports the idea that the 3.0- to 3.3-year periodicity is connected with a real phenomenon and is not just a result of sampling fluctuations.

On the other hand the peak at 2.15 years behaves differently. It is altogether absent in the second sub-period (1900–01 to 1953–54). This finding has several possible consequences: (1) the peak may be due to sampling fluctuations; (2) the peak may be associated with the Q.B.O. In that case the implications are either that the Q.B.O. may not be always manifested by rainfall fluctuations in the Eastern Mediterranean or that the Q.B.O. itself is not a regular phenomenon and therefore is not manifested in the rainfall for the second period. More studies are needed to answer these questions.

The possibility of using prominent peaks in the spectrum to predict the long-range behaviour of the annual rainfall is attractive. In the case of the 3.0- to 3.3-year peak such an idea is promising because the partial variance in the vicinity of 3.0 to 3.3 years constitutes a relatively large percentage of the total variance. Even if such attempts fail studies of the kind reported here may help to improve our understanding of basic oscillatory features in the general circulation of the atmosphere such as the S.O. or the Q.B.O. More work is needed to establish in more detail the connection between the rainfall in the Eastern Mediterranean and these types of global oscillations.

5. Acknowledgements

The author wishes to thank Professor Louis Berkofsky for carefully reading the manuscript and for some important suggestions. Thanks are also due to Miss Perla Druian for performing some of the calculations and to Mrs Henia Simon for typing the manuscripts.

REFERENCES

Angell, J. M. and Korshover, J. 1977. Estimates of the global change in temperature, surface to 100 mb between 1958 and 1975. *Mon. Wea. Rev. 105*, 375–385.

Bjerknes, J. 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev. 97*, 163–172.

Blackman, R. B. and Tukey, J. W. 1959. *The measurement of power spectra: from the point of view of communications engineering*. New York: Dover Publications, Inc.

Charney, J. G. 1975. Dynamics of deserts and draught in the Sahel. *Qt. Jl. R. met. Soc. 101*, 193–202.

Chiu, Wan-Cheng. 1967. On the interpretation of the energy spectrum. *Am. J. Phys. 35*, 642–648.

Gabriel, K. R. and Kesten, H. 1963. Statistical analysis of annual rainfall in Jerusalem. *Bull. Res. Coun. Israel. 11G*, 142–145.

Granger, O. E. 1977. Secular fluctuations of seasonal precipitation in lowland California. *Mon. Wea. Rev. 105*, 386–397,

Landsberg, H. E., Mitchell, Jr., J. M. and Crutcher, H. L. 1959. Power spectrum analysis of climatological data for Woodstock College, Maryland. *Mon. Wea. Rev. 87*, 283–298.

Munk, W. H., Snodgrass, F. E. and Tucker, M. J. 1959. Spectra of low-frequency ocean waves. *Bull. Scripps Inst. Oceanog. non-tech. Ser. 7*, 283–362.

Namias, J. 1969. Seasonal interaction between the North Pacific Ocean and the atmosphere during the 1960's. *Mon. Wea. Rev. 97*, 173–192.

Neumann, J. 1956. On the incidence of dry and wet years. *Israel Explor. J. 6*, 58–63.

Otterman, J. 1974. Baring high-albedo soils by overgrazing, a hypothesized desertification mechanism. *Science, N.Y., 186*, 531–533.

Rodhe, H. and Virji, H. 1976. Trends and periodicities in East African rainfall data. *Mon. Wea. Rev. 104*, 307–325.

Roseman, N. 1955. One hundred years of rainfall in Jerusalem. *Israel Explor. J. 5*, 137–153.

Trenberth, K. E. 1976. Spatial and temporal variations of the Southern Oscillation. *Q. Jl. R. met. Soc. 102*, 639–653.

Troup, A. J. 1965. The 'Southern Oscillation'. *Q. Jl. R. met. Soc. 91*, 490–506.

Wagner, J. A. 1971. Long-period variations in seasonal sea-level pressure over the Northern Hemisphere. *Mon. Wea. Rev. 99*, 49–66.

White, W. B. and Clark, N. E. 1975. On the development of blocking ridge activity over the Central North Pacific. *J. Atmos. Sci. 32*, 483–502.

Winstanley, D. 1973. Rainfall patterns and general atmospheric circulation. *Nature, Lond. 245*, 190–194.

Zangvil, A. 1977. On the presentation and interpretation of spectra of large-scale disturbances. *Mon. Wea. Rev. 105*, 1469–1472.

ВРЕМЕННЫЕ ВАРИАЦИИ ГОДОВЫХ ОСАДКОВ В ИЕРУСАЛИМЕ

С помощью спектрального анализа и частотных фильтров изучаются годовые суммы осадков в Иерусалиме за период с 1846–7 по 1953–4 годы. Затем демонстрируется влияние различных методов снектральных представлений. Заметный значимый пик в спектре имеется на периодах 3–3.3 года и вторичный пик виден для 2.15 лет. Более 55% полной изменчивости годовых осадков в Иерусалиме сконцентрировано в интервале периодов между 2 и 4.3 года. Эти два пика были сравнены с опубликованными спектрами осадков и других метеорологических параметров в других частях света и было найдено, что они сопоставимы с Южными колебаниями и квази-двухлетними колебаниями, соответственно. Когда данные были разделены на два равных подпериода, то пик на периодах 3.0–3.3 года остается доминирующей особенностью в обоих спектрах, в то время как второй пик исчез полностью из второго подпериода. Обсуждаются следствия этого поведения.