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REVIEW

Temporal variations of rainfall in Israel

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ABSTRACT: This paper is a summary of relevant studies dealing with the analysis of the temporal rainfall variability in Israel. The diurnal patterns of rainfall differ between the southern and northern regions of the country. The spatial distribution of seasonal rainfall depends on the chosen time interval. While the monthly means exhibit a 1-peak sinusoidal pattern, averages over shorter intervals reveal more complicated functions. The various definitions of rain spell enable us to gain better insight into their annual and interannual distributions. Due to the lack of prolonged rainfall data from a reasonable number of stations, the study of rainfall periodicity, long-range contemporary rainfall variation and future scenarios will have to wait for further data to be accumulated.

KEY WORDS: Rainfall · Temporal variations · Rain spells · Israel

INTRODUCTION

In a separate paper (Goldreich 1994) the annual spatial distribution of rainfall in Israel was analyzed. In this paper, the temporal changes at various time scales are discussed.

Israel is situated between 29.5° and 33.5° N along the southeastern Mediterranean coast (Fig. 1). The country can be divided into 4 longitudinal physiographical strips (from west to east): (1) the Coastal Plain; (2) the hilly regions, including (from north to south) Galilee (highest summit 1208 m), Shomeron (945 m), Jehuda (1020 m) and Negev (1045 m); (3) the Jordan Rift Valley; and (4) the Golan Heights.

Extra-tropical cyclones reach Israel mainly during the winter months and less during the transition seasons, with showers along the cold front (and in the cold air mass which follows this front) being the typical precipitation. Fig. 2 shows the map of annual rainfall for Israel. Of the annual rainfall, 65% occurs during the 3 mo period of December to February. During the summer months (June to August), there is no precipitation (the mean is nil!). In this respect, Israel experiences the extreme case of Mediterranean climate. Snow is uncommon; if it occurs it is generally confined to the tops of hills. Jerusalem (800 m) has an annual average of 2 d of snow.

The aim of this study was to summarize the research carried out on the temporal distribution of rainfall in Israel at various time scales. The importance of this paper lies in the geographic location of Israel, where proximity of the Mediterranean climate to the semi-arid and arid regions makes the research, the approach and the results interesting to the community of international climatologists.

DIURNAL RAINFALL DISTRIBUTION

In contrast to tropical and monsoonal lands, where the diurnal rainfall pattern shows a clear cycle with a rainfall depth peak in the afternoon hours, in extra-tropical regions, it is hard to find any clear diurnal pattern in rainfalls related to cold frontal zones and mid-latitude cyclones. Katsnelson (1955), who reviewed this topic, presented hourly data from recording rain gauges for Tel-Aviv and Ramle (Fig. 1). The maximum accumulation values were recorded from 04:00 to 05:00 h and from 05:00 to 06:00 h, respectively. Katsnelson (1955) did not try to explain these maxima, but mentioned that this is a maritime type of diurnal cycle. On the other hand, at inland remote stations, the diurnal pattern is different. Recently, a comprehensive study of rainfall intensity in Israel (Morin et al. 1994)

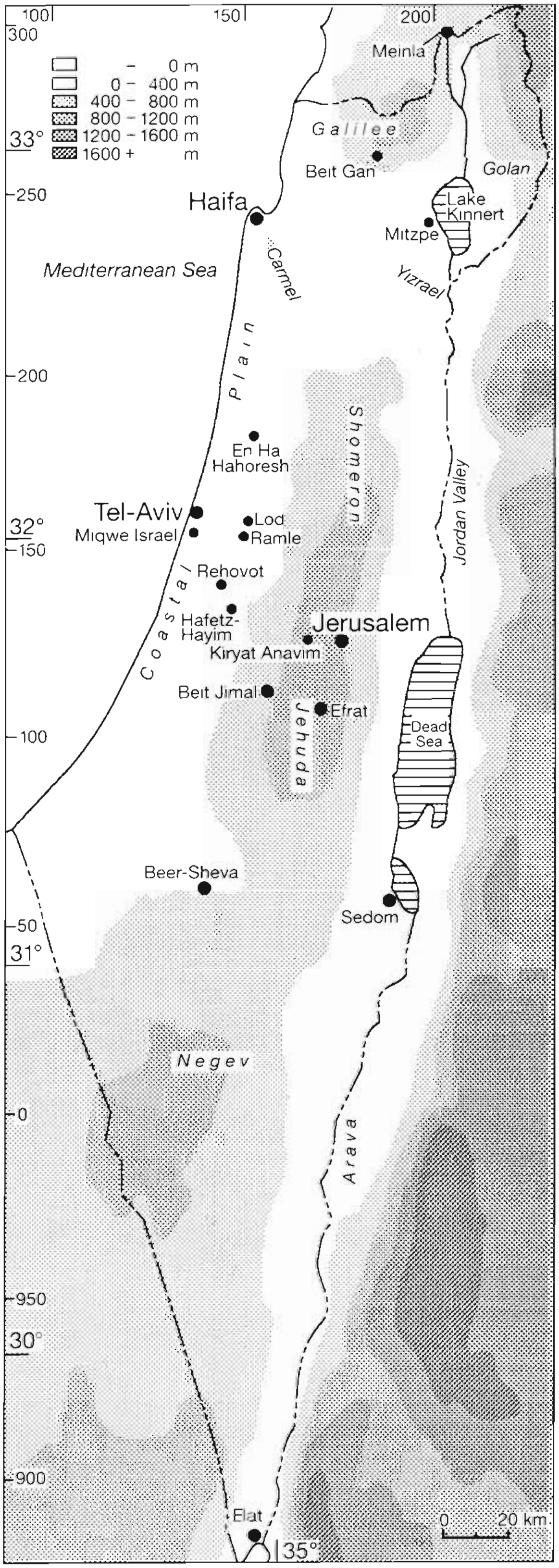

Fig 1 General topographical map of Israel with regions designated Coordinates are given as longitude and latitude and as local Israeli grid coordinates (1 unit = 1 km)

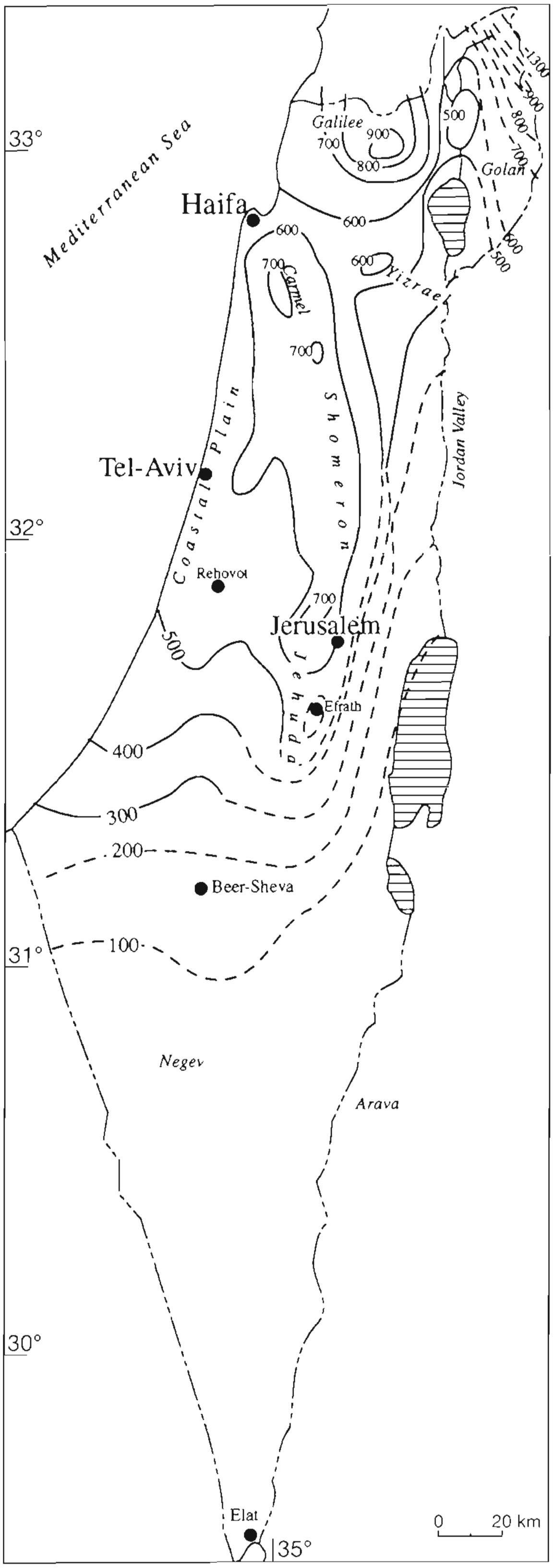

Fig. 2 Annual normal rainfall map of Israel, 1961 to 1990 (IMS 1990)

included the diurnal variation of rain amount. That study only presented the graphs, as the data are still being analyzed. However, it can be deduced that along the Mediterranean coastline there is a weak near-dawn maximum, which weakens with distance from the shore and diminishes in the hilly region. In the desert areas and in the Jordan Valley the maximum is in the afternoon, as shown later in this section.

There are 3 possible explanations for these near-dawn maxima: (1) Following Neumann's (1951) explanation for the frequent nocturnal thunderstorms in Lod (Fig. 1); the easterly land breeze may converge with the westerly synoptic flow, and consequently, could promote the vertical flow component. This phenomenon was verified in a 2-dimensional cloud ensemble model (Khain et al. 1993). It was found that convergence of westerly gradient wind with weaker land breeze can cause rainfall in the Coastal Plain. (2) In stable conditions, the near-saturation air advected landward may become cooler over the land and reach saturation during these hours of temperature minimum. This process might produce some stratiform clouds which eventually would bring some light rain. Accumulation of such predawn rainfall, together with the usual frontal rain, might create a diurnal rainfall peak in stations adjacent to the sea shore (Goldreich 1995b). (3) During unstable conditions, at the time when the cold front or the cold airmass cross the shoreline, the nocturnal urban heat island, which is most intensive at these hours, may increase the instability and thus increase the rainfall (e.g. Goldreich & Manes 1979, Goldreich 1995a).

Some studies have examined the diurnal pattern of the rainfall intensity. Katsnelson (1955), who examined Tel-Aviv, Ramle, Haifa (Technion) and Aman (in Jordan), concluded that there is no clear diurnal pattern of maximum and minimum intensity. However, in the Negev Desert there is a distinct maximum in the afternoon (Kutiel & Sharon 1980) which is related to convective rainfall. Fig. 3 presents the 10 yr means of the diurnal rainfall patterns for intensities both above and below 30 mm h^{-1} for 5 stations in the Negev. The diurnal pattern of 'normal' rainfall (<5 mm h^{-1}; see Fig. 3), connected with the passages of cold fronts, shows little variability. The situation in the Negev Coastal Plain is 'hybrid'; during the autumn months of September to November 'desert conditions' dominate and the maximum is during the day, while during the rest of the rainy season nocturnal rainfall is more pronounced (Otterman & Sharon 1979, Kutiel & Sharon 1980). Otterman & Sharon (1979) also explained the nocturnal rainfall excess here by invoking Neumann's (1951) reason for a maximum in nocturnal thunderstorms in Lod, emphasizing that the coastline along the Negev is more concave than at Lod, thus the convergence of the land breeze is amplified significantly in the Negev.

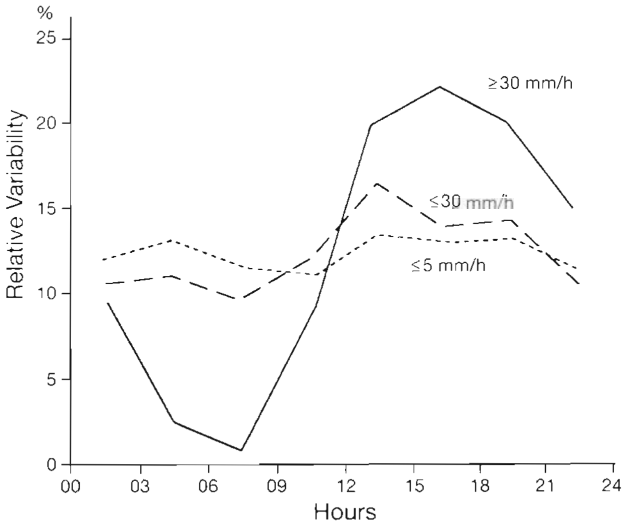

Fig. 3. Diurnal variation of rainfall with high and low intensity in the Negev (after Kutiel & Sharon 1980)

Morin et al. (1994), who presented figures of the diurnal patterns of various rainfall intensities, revealed a most complex spatial and temporal variation. Generally speaking, the data agree with the results mentioned above; however, the study is not yet complete and one should wait for more exact conclusions.

INTER-ANNUAL RAINFALL DISTRIBUTION

Length of the rainfall season

Officially, the 'rainfall year' is from 1 August to 31 July. This arrangement is most convenient, since the year begins in the middle of the dry summer, when the normal average rainfall is nil. It is also convenient for measuring the rainfall depth in the desert areas, where many of the annual rainfall collectors (a special gauge fitted for a uni-annual observation) are spread over inaccessible remote areas. Almost any date during the summer can be chosen for the annual measuring expedition without adversely affecting the accuracy of the measurements.

The actual rainfall season is much shorter than the 'rainfall year' It generally starts in mid October and ends in early May. Concerning the issue of a spatial difference in the length of the rainy season, 2 positive but contradicting answers have been given. Katsnelson (1968) maintained that the season is shorter towards the south, i.e. in the Negev the season commences in November and terminates generally in April. Kutiel (1985) reached a contradictory conclusion: the season starts earlier in the Negev and ends later. The explanation for this apparent disagreement is that while Katsnelson (1968) referred to rainfall quantities in the fringe months, Kutiel (1985) referred to the frequency distribution of dry spells (an interesting parameter which will be discussed later). Based on harmonic analysis, he calculated the duration (in days) between dry spells and referred to the time interval between the first and the third minimum (of the third harmonic) of the rainy season; these intervals are longer toward the south. This was checked with the aid of 2 additional parameters: the mean date of the first 5 mm accumulation and the mean date when AR - 5 (mm) has accumulated, where AR is the annual rainfall amount (see Atlas of Israel 1956; this map was excluded in later editions). These dates are 5 October and 15 May in the Galilee and 15 November and 25 April in the Negev. Obviously, according to these parameters, the rainy season is shorter to the south.

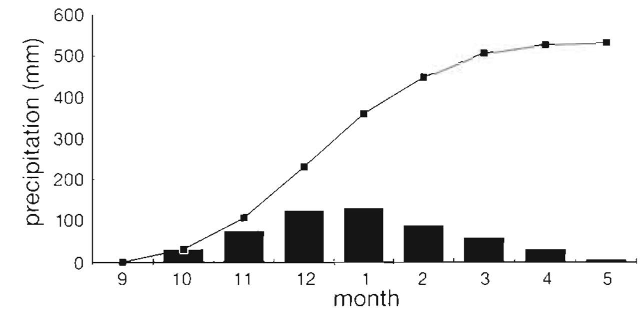

Fig. 4. Histograms and accumulation of mean monthly rainfall distribution at Hafetz-Hayim, 1961 to 1990 (IMS 1990)

Intra-seasonal variation on a monthly basis

The average annual patterns of rainfall in Israel by month are quite simple: rainfall increases until January and decreases thereafter. The mid-season months are December to February; by February almost two-thirds of the annual rainfall has accumulated (Fig. 4). Autumn and spring each account for about 15% of annual rainfall. Fig. 5 presents the seasonal pattern of accumulated rainfall in Tel-Aviv and Jerusalem. Mid-season (50% accumulation) occurs earlier in Tel-Aviv by 20 d (Goldreich 1990). The mean monthly rainfalls are symmetric around the mid-season peak and have a sinusoidal shape, therefore harmonic analysis (Fourier transformation) can be applied to the data where the first harmonic explains more than 90% of the monthly rainfall variance (Goldreich 1990). Further discussion of the hilly area mid-season lag (probably at variance with all other Mediterranean climate regions) shown in Fig. 5 is presented elsewhere (Goldreich 1994).

Intra-seasonal variation on a non-monthly basis

Monthly average distribution is a convenient parameter from both the technical and administrative points of view. In the previous section it was shown that the annual pattern of rainfall is well organized in a clear simple bell- or sinusoidal-shaped pattern (Fig. 4). However, rainfall histograms with shorter time intervals are not that simple. It seems that the monthly distribution is not a delicate enough parameter and obscures some of the variations in shorter intervals. Fig. 6 demonstrates the extreme case where the mean values of the daily rainfall show a very irregular seasonal pattern. This station (En Ha Horesh), located in the Central Coastal Plain, reveals a bi-modal or even a multi-modal seasonal rainfall variation. At a first glance, one may argue that this 20 yr sample is too short, and increasing the observation period could transform these spike-shaped singularities to a smoother, simpler pattern, similar to that in Fig. 4. This argument is supported by Brier et al. (1963), who analyzed independent series of daily precipitation data in the U.S. and demonstrated that there is no statistical tendency of precipitation concentration near certain dates. Yet, these findings contradicted many other studies which showed a recurring tendency of some weather parameters around specific dates in the calendar. Such singularities have been found for longer periods in North America and Europe. Barry & Perry (1973, p. 291-294) discussed these singularities comprehensively, but did not come to any definite conclusion concerning their existence.

Examining Fig. 7, which is based on a longer data period than that of En Ha Horesh, shows that a 10 d average distribution does not have unimodal characteristics. According to Fig. 4, at the peak of the rainfall season (late December and early January), there is a distinct rainfall decrease. A further rainfall decline is evident in late February.

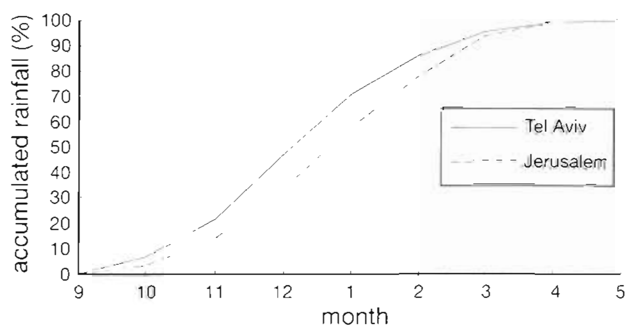

Fig. 5. Mean annual pattern of accumulated monthly rainfall at Tel-Aviv (solid line) and Jerusalem (dashed line), 1961 to 1990 (IMS 1990)

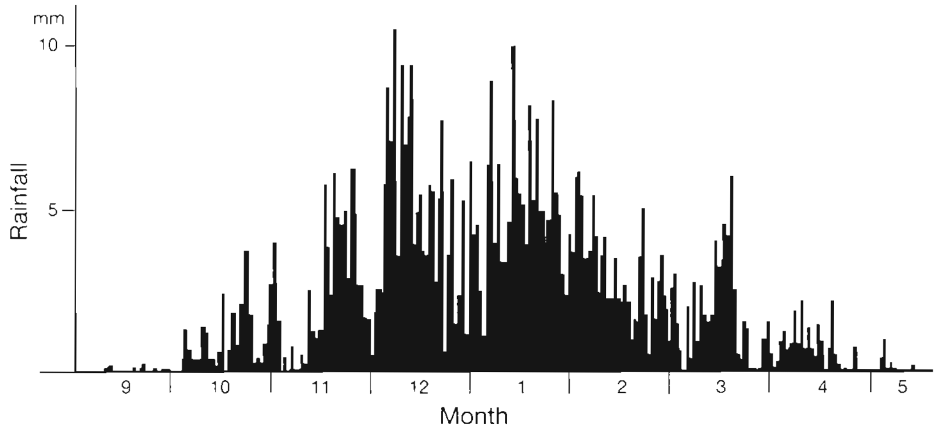

Fig. 6. Mean daily rainfall distribution at En Ha Horesh, 1958 to 1977 (after Kutiel 1985)

The idea of applying decade partitioning is not new. Lomas et al. (1976) published normals and probabilities for rainfall periods in 1950 to 1975 for 10 d, 20 d and 1 mo in which some singularities in the rainfall season were revealed. This phenomenon was comprehensively studied by Ronberg (1984), who used it as a basis for a new division of 10 d groups into 'active' and intermediate 'settled' sub-seasons. Moreover, Ronberg (1984) attributed a characteristic synoptic condition to each of these sub-seasons. It is interesting to note the similarity between the subseasons and the frequency of upper troughs in the Levant Coast and the south-north oscillations of the sub-tropical jet stream. In each of the 'active' sub-seasons, the atmospheric circulation includes the influence of an upper trough and the southward penetration of the jet stream. In 'settled' sub-seasons, the sub-tropical jet stream retreats northward and the upper air trough moves eastward (Sharon & Ronberg 1988). Fig. 8 presents the frequency of Cyprus cyclones according to the decade sub-periods for the years 1965 to 1970. These findings were confirmed by the 500 hPa data of the Mediterranean Basin and the Atlantic Ocean for 10 yr (Jacobeit 1988). Fig. 9 shows the 10 yr relative frequency of the upper air trough in the Eastern Mediterranean Sea.

Dividing daily rainfall into 10 d periods, similar to the monthly data, while logical and convenient, is not necessarily ideal. For instance, Sharon & Ronberg (1988) found the division into groups of 6 d to be superior. Fig. 10 presents hexads (6 d) rainfall average amounts for 10 yr at 4 central Coastal Plain stations. Two board peaks of abundant rainfall in December and January about 40 to 45 d apart can be discerned. In contrast to the 10 d division, in the hexads there are some more distinct oscillations in autumn and spring. From February onwards the rhythm changes to shorter oscillations of about 25 d. The high frequency of peaks in autumn and spring in contrast to winter is attributed to the small number of long upper air troughs (Rossbi waves) which dominate the synoptic situation in winter. Short waves are typical in autumn and spring (Sharon & Ronberg 1988). The most suitable time interval is a subject with several interesting facets and still needs to be investigated.

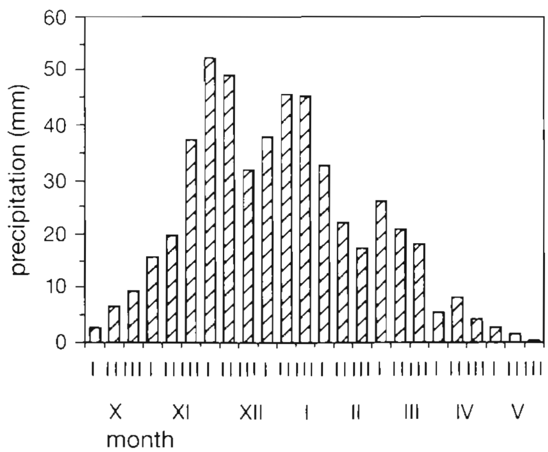

Fig. 7. Histogram (10 d intervals) of mean rainfall at Hafetz-Hayim, 1946 to 1979 (after Stiefel 1982)

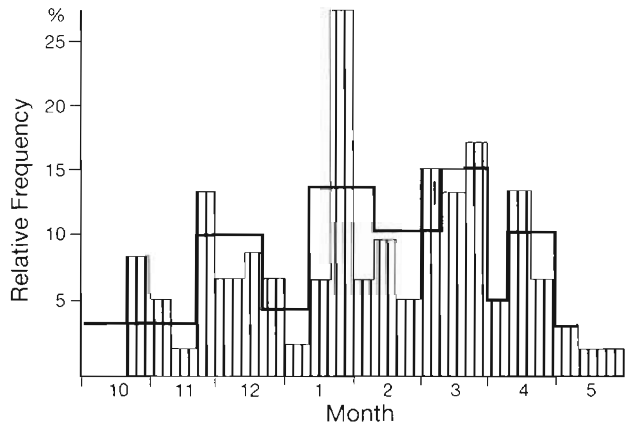

Fig. 8. Relative frequency of Cyprus cyclones in the vicinity of Israel, 1965 to 1970), for 10 d periods and sub-seasonal intervals (after Sharon & Ronberg 1988)

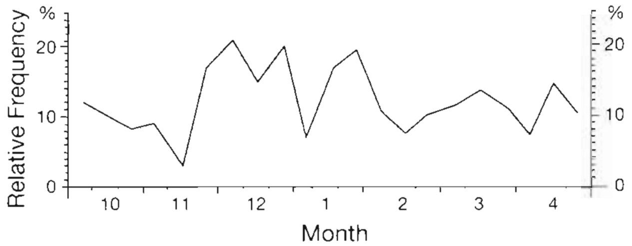

Fig. 9. Relative frequency (10 d intervals) of 500 hPa troughs in October-April 1966 to 1976 in the eastern Mediterranean (after Jacobeit 1988)

Wet and dry spells

An important applicative approach to rainfall statistics is the wet/dry spell distribution. A rain spell is defined as a consecutive group of rainy days, and a dry spell as the period between 2 rain spells. A rainy day is defined in Israel as a day where at least 0.1 mm rain is measured. A rain cycle is a rain spell followed by a dry spell. The statistical results may differ if the set of rain cycles starts with a dry spell.

D. Ashbel (pers. comm.) estimated that rain cycles average about 7 d. Neumann (1955) checked 27 yr of Tel-Aviv rainfall data and also found the mean rain cycle length to be 7 d. However, the mode was 5 d (for a rain spell followed by dry spell). Further statistical analysis showed this parameter to have a geometrical frequency distribution (Gabriel & Neumann 1957) and that rainy days can be fitted to the Markov Chain probability model (Gabriel & Neumann 1962). When the number of days in the cycle was checked for the reverse sequence (dry spell first), the mode was 4 d for Tel-Aviv and Jerusalem data (Katsnelson 1956). The most frequent rain spell length was 1 d, and the mean is 2.5 d. Rain spells are shorter at the beginning and the end of the rainy season and longer in mid-season;

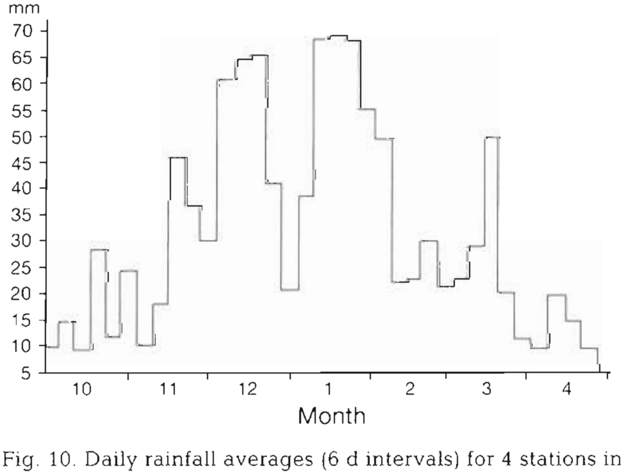

Fig. 10. Daily rainfall averages (6 d intervals) for 4 stations in the northern part of the Central Coastal Plain, 1963 to 1972 (after Sharon & Ronberg 1988)

this fits the cyclone and upper air trough speed movement over Israel mentioned in the previous section. Rain spells lasting longer than 10 d are rare. The previous record of 16 d [in Tel-Aviv and Anabta (Western Shomeron) measured during 21 December 1941 to 5 January 1942] was recently broken during the exceptionally rainy year 1991–1992 (17 d at the University of Haifa, 28 January to 13 February 1992; Kutiel 1992, pers. comm.).

Dry spells are much longer. Periods of more than 1 mo without rain, even in the middle of the rainy season, are not rare events. Kutiel (1985) checked the annual pattern of dry spells and found it to be trimodal. This supports the proposition that a non-monthly sub-season division of the data is more rational and meaningful than conventional monthly means. Since dry spells complement rain spells, they are expected to have the opposite distribution: longer dry spells at the beginning at the end of the rainy season and shorter spells during mid-season.

Another important parameter is the annual number of rain spells. At the end of the last century it was found that there were 23 rain spells during a season in Jerusalem, and very seldom did the length of the rain spell exceed 8 d (Chaplin 1883). Striem & Rosenan (1973), who re-examined this data, showed the mean number of rain spells to be 25.2, similar to Neumann's (1955) finding of 25.5.

A different definition for rain spell was introduced by Striem & Rosenan (1973) whereby the 'rainfall day' does not commence at 08:00 h local standard time (or 06:00 h UTC) but rather at the hour of initial accumulation. Additionally, according to this definition, a short break of 1 or 2 'dry days' does not constitute a termination of the rain spell (if the synoptic system does not change). Thus, 2 rain episodes separated by a short interruption would be considered as 1 long rain spell. Table 1 summarizes the distributions of such rain spells over a 20 yr period in Jerusalem. The data have been sorted according to annual rainfall amount into 5 yr groups. Based on the definition of Striem & Rosenan (1973), the mean annual number of rain spells is 17.2. Table 1 reveals the differences between wet and dry years not to be dependent on the number of rain spells, but rather on the average rainfall amount for each rain spell. The number of rain spells with less than 50 mm during a given season was almost constant over the 20 yr, averaging 14 spells with a mean deviation of 2. These light-to-moderate precipitation events contributed 187 mm to mean annual accumulation. On the other hand, the frequency of rain spells with more than 50 mm varied considerably: 5 to 6 rain spells in 'wet' years versus 1 in 'dry' years. Rain spells with more than 50 mm and longer than 48 h can be divided into 2 groups: (1) those less than 100 mm, with mode

Table 1. Mean annual rainfall, number of rain spells and of rainy days, and daily rainfall amount in 4 groups of years by annual rainfall amount in Jerusalem (after Striem 1981 and Striem & Rosenan 1973). Rainfall given in mm

Groups of years	Annual rainfall	Average no. of rain spells					Rain days	
		Total	≤22.5 mm	>22.5 mm	≤50 mm	>50 mm	No.	Average rainfall
5 rainiest years	683	19.2	11.4	7.8	13.6	5.6	66	10.3
5 years above average	560	17.2	10.6	6.6	13.4	3.8	61	9.2
5 years below average	437	16.6	12.0	4.6	14.2	2.4	53	8.2
5 driest years	270	15.6	12.2	3.4	14.6	1.0	46	5.9

of 70 mm and mean duration of 63 h, and (2) those with more than 100 mm, all longer than 3 d with mode of 5 to 6 d. Striem & Rosenan (1973) thus deduced that the difference between dry and wet years does not necessarily depend on the number of cyclones which reach the Levant coast, but on their intensity.

Striem (1981) continued to study the rain spells and found that in longer spells, amount and intensity increase. The intensity was greater with respect to daily amount (see Table 1) and the number of rainfall hours per day. Moreover, during a rain spell the peak of daily amount tended to occur on the second rainy day, not the first (Table 2). As for the seasonal distribution, he found that in short spells (1 to 2 d) during the mid-season (January to March) hourly rainfall intensity was lower than those at the beginning or the end of the season. These same findings were made by Katsnelson (1955). The connection between rain spell length and rainfall intensity was expressed by Striem (1981) as:

$$Q = Q_0 t^m \quad (1)$$

where Q is rainfall amount (mm), Q_0 = 0.15 mm $h^{-4/3}$, t is rain spell length (d or h) and m = 4/3. In terms of intensity (i; Q/t), the relationship is:

$$i = i_0 t^{m-1} \quad (2)$$

where $i_0 = Q_0/t$. Eq. (2) is applicable for both the length of the rain spell (in days) and for the number of the rainy hours in the spell.

After analyzing October to April rainfall at several locations over 30 yr (1951 to 1980), Tzvetkov et al. (1985) reached the same conclusion: the number of rain spells was approximately constant over the years. They defined a rainy day as one in which rain was recorded for at least 3 of 4 cities (Haifa, Tel-Aviv, Jerusalem and Beer-Sheva). According to this definition, the difference between wet (17.3 rainy days) and dry (16.25 rainy days) years was even smaller than that found by Striem & Rosenan (1973). Thus, the Tzvetkov et al. (1985) support the notion that the difference between dry and wet years is in the length and intensity of rain spells, not in their number.

It was interesting to investigate rain spells with more than 100 mm. Using observational data collected at the station Hafetz-Hayim covering a period of 45 yr, 47 such events could be discerned (about 1 yr^{-1}). However, closer inspection revealed that no heavy precipitation spells occurred in 13 yr, 1 event in 20 yr, 2 events in 9 yr and 3 events in 3 yr (Stiefel 1991). The 'rainiest' rain spell occurred in November–December 1991, when an accumulation of 322 mm in 7 d was recorded at Hafetz-Hayim.

INTERANNUAL RAINFALL VARIATIONS

The annual rainfall distribution, at locations where the mean exceeds 500 mm, are among the several climate parameters which are distributed 'normally' (Linacre 1992). However, in Israel this interannual rainfall distribution, as in some other countries, does not have a perfect normal (Gaussian) distribution, but displays a positive asymmetric feature. The relevant annual statistics for rainfall over 100 yr at Jerusalem are: mean = 560 mm, mode = 480 mm, median = 544 mm, and SD =142 mm (Rosenan 1955). Neumann (1956) and Gabriel & Kesten (1963) preferred the Pearson Type III distribution as the most suitable function for describing Jerusalem rainfall. However, the deviation of Jerusalem's interannual rainfall distribution from a normal distribution was not significant (5% level) since the asymmetry ($b^{1/2}$) was 0.466 and the kurtosis was 0.788 (Gabriel & Kesten 1963). The rainfall data for Beer-Sheva similarly exhibited a near-normal distribution (Shashoua 1977). The same was found by Lomas &

Table 2. Mean daily rainfall (mm) and hourly intensities (mm^{-1}) as functions of rain-spell duration (d) (after Striem 1981)

Length of rain spell:	Daily rainfall 1	2	3	4	Daily intensity 1	2	3	4
1st day	6.1	7.9	10.4	7.0	1.17	1.27	1.45	0.95
2nd day		7.3	13.9	19.4		1.09	1.25	1.72
3rd day			7.1	12.8			1.13	1.42
4th day				7.5				1.50

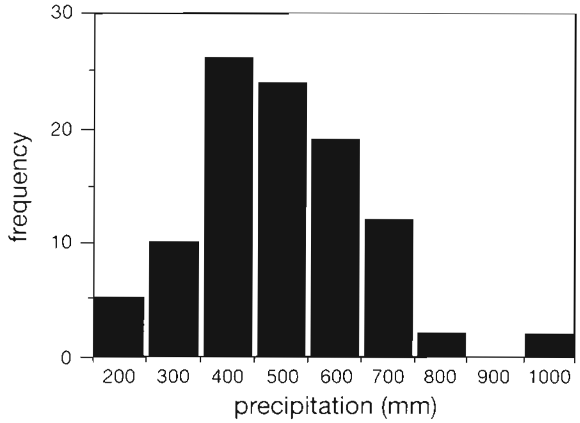

Fig. 11 Frequency distribution (100 mm intervals) of mean annual rainfall accumulations at Jerusalem (after Goldreich 1995b)

Rinburg (1991) for a reconstructed long rainfall series for Nablus (in the middle of Shomeron, mean 666 mm); however, they did not mention if any 'normality test' was applied. A comprehensive study, which included 50 rain series stations, was performed by Rosenberg (1990). He demonstrated (with χ^2 test), that, except for Mitzpe (adjacent to the western coast of the Kinneret Lake), all of the series fit the normal distribution (with 5% significance) and that this distribution was preferable to Pearson type III, log-normal and log-Pearson III distributions.

Although the results of the various statistical tests confirm the validity of the normal distribution with respect to interannual rainfall, some caution should be taken in applying Gaussian statistics to the data. For instance, due to positive asymmetric distribution, the use of standard deviation to predict probable values (above or below a certain threshold) is not recommended. However, if one refers to annual rainfall volume for the entire country (accumulation multiplied by surface area; see Stanhill & Rapaport 1988), the multi-year record fits a normal distribution quite well: mean = 7.916 km^3, median = 7.78 km^3, mode = 7.8 km km^3. The reason that the distribution is more normal at this scale is because a larger set of values has been averaged. For example, the coefficient of variation for Jerusalem alone is 28.4%, while the value for the national volume is 24.4%.

The interannual rainfall histogram with 100 mm intervals (Fig 11) shows 1 prominent peak, differing from the histogram with 30 mm intervals which shows 5 or 6 peaks (Fig. 12). When the 118 Jerusalem rainfall years were divided into 2 subsets, their histograms had the same numbers of peaks (Striem 1967a, b), showing that the statistics for the 2 periods were similar.

Rainfall variability maps, showing the spatial distribution of the coefficient of variation (CV), have been prepared by 3 researchers [Katsnelson 1964 (1921 to 1950), Sharon 1965 (1947 to 1962), Rosenberg 1990 (1931 to 1970)]. In most of the country CV values were between 20 and 40%. CV increases with distance from the Mediterranean Sea and increases southwards. (Fig. 13). Relative variability (RV) values are somewhat lower than those of CV. RV for Elat is 52% (for 10 yr); this fits the RV global statistical model introduced by Conrad (1941):

$$RV = 3600/(P+60) + 13 \quad (3)$$

where RV is in percent and P is mean annual rainfall (mm). By inserting Elat annual rainfall (30 mm) in Eq. (3) we obtain RV = 53%.

The relationship between annual rainfall and annual mean temperature was studied by Striem (1974). He showed that, for Jerusalem data, rainfall accumulation was greater during colder winters (108 mm per °C). High correlation coefficients were obtained even when the rainfall series was divided into 2 subsets and regressed separately. One has to be careful not to ascribe a cause-and-effect relationship to this finding. In fact, both variables are mostly determined by a third variable — the frequency of polar air mass penetration into the eastern Mediterranean region. Such deep penetrations shift the cyclone to a more southerly trajectory accompanied by cold, unstable air masses which increase rainfall and lower air temperature. The temperature reduction is also maintained by the cloudiness which accompanies rain spells. This temperature-rainfall relationship is in contrast to positive correlations in many other regions throughout the world. It is quite usual to expect higher temperatures to induce convective rainfall at many subtropical humid locations. Under these circumstances rain generally falls in the warmer afternoon hours during the summer

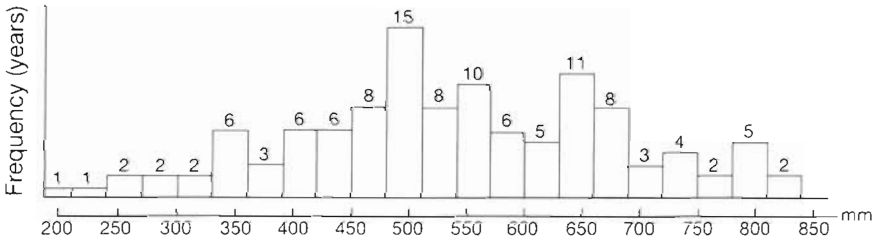

Fig. 12. Frequency distribution (30 mm intervals) of mean annual rainfall accumulations at Jerusalem (after Striem 1967b)

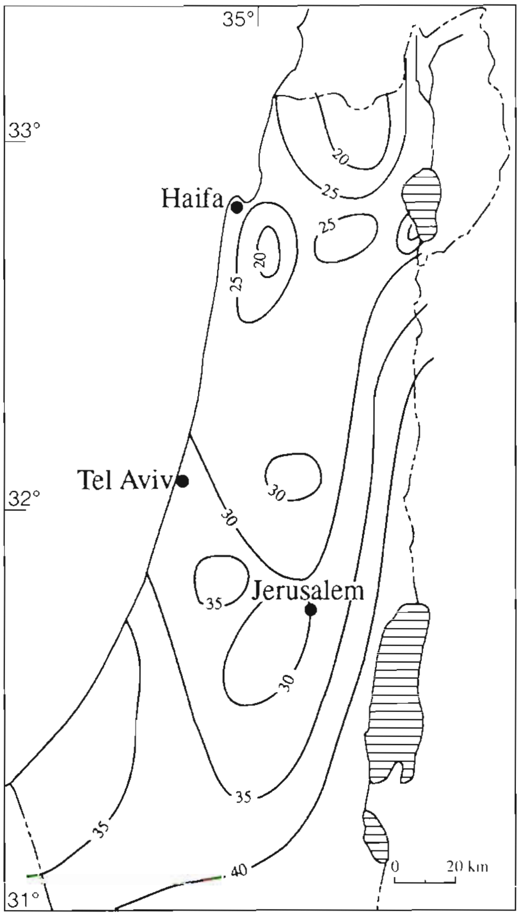

Fig. 13. Map of the coefficient of variation (%) for rainfall, 1931 to 1970 (after Rosenberg 1990)

Monthly interannual rainfall variations

The interannual variability of the monthly rainfall exceeds the variability of the annual means. While there is no record of an entire season without rainfall, rainless months have previously occurred in each of the rainy season months for the whole country, with the exception of January. However, several stations in the Lower Galilee were completely dry in January 1955 (Katsnelson 1956). It is rare for December and February to be dry, but such prolonged breaks in precipitation have occurred relatively often during the transition months October, November, March, April and May. The frequency of dry months increases from January onward.

A list of the extreme maximum monthly precipitation accumulations is given in Table 3. In some cases the monthly value of a particular year exceeds the long-term annual mean for the station. In rare cases, the rainiest month of certain years has even been October or May. For instance, in Sedom (at the southern tip of the Dead Sea) rainfall in October 1943 was 57 mm, and in Mitzpe (adjacent to the western coast of Lake Kinneret) rainfall in May 1923 was 109 mm. It is worthwhile to mention that both stations are located in the Jordan Rift Valley, where high rainfall intensities caused by the Red Sea trough are frequent in the transition season. The data in Table 3 provide additional evidence that the main portion of the rainfall occurs in the Coastal Plain during the first part of the rainy season (up to December) and only later on is significant precipitation displaced to the hilly region. Examples of extreme monthly accumulations were found during the 1991–1992 rainfall season; recorded precipitation was 1607 mm at Metula (at the northern tip of the Upper Galilee) and 1537 mm (280% of the mean annual rainfall!) at Havatzelet (near Rehovot). A summary of this rainfall year was done by Gat & Rubin (1993).

'The last rainfall year was an unusual one'. Such a phrase, often heard from layman and climatologist alike, generally refers to the annual amount and to the seasonal pattern. In how many years are the mean annual rainfall and the seasonal march of accumulations similar to the long-term means? Never. A 'normal year' is a statistical entity that does not exist. Efrat (1962) examined the homotopic rainfall series of Jerusalem, compiled by Rosenan (1955), sorting the annual patterns of rainfall into 16 types. Even type c, which resembled the annual distribution with maxima in 2 adjacent months, occurred only 3 times, but in none was the annual sum closer than 1 SD to the annual mean (Goldreich unpubl.). After comparing data from Jerusalem to those from Miqwe-Israel (at the southeastern outskirts of Tel-Aviv), Efrat (1962) came to the conclusion that there was a substantial spatial variation of his 'rainfall types'.

Table 3. Maximum monthly rainfall records in Israel (mainly after Katsnelson 1956 and Gat & Rubin 1993)

Month	Year	Station	Rainfall (mm)
October	1942	Lod	199
November	1938	Ramat-Gan[a]	432
December	1991	Havazelet[b]	628
January	1969	Magdal Shams[c]	846
February	1857	Jerusalem	463
March	1953	Qiryat Anavim	329
April	1949	Misgav-Am[d]	263
May	1946	Bet-Gan	133
June	1992	Bet-Gimal	48

[a] Adjacent to Tel-Aviv
[b] Adjacent to Rehovot
[c] In the Golan Heights; at the peak of the Upper Galilee (Mt. Miron, 5 km east of Bet-Gan) the record was 744 mm
[d] SW of Metula

Seeking a rainfall periodicity

Discovering climatic parameter cycles has been the main goal of many climatologists in various countries over the years. Considerable effort and resources have been devoted to this purpose, mainly stressing the rainfall and temperature periodicity. In order to discourage the continuation of this fruitless endeavor, the World Meteorological Organization (WMO) at the UNESCO Rome 1963 conference advocated a total abandonment of the search for periodicity, which was declared to be non-existent. One cannot say that the recommendation has been accepted by the climatologist community: this fascinating topic still intrigues many investigators. South Africa is one of the odd regions where a periodicity of 18 to 20 yr was detected, being composed of about 9 to 10 consecutive rainy years followed by a similar number of dry ones (Tyson 1986). Nevertheless, since evidence of this cycle was published, researchers have not been able to predict rainfall anomalies for an isolated year or for a specific site with a high level of probability. They can only state with a given probability what the general pattern will be in the next 10 yr for the entire relevant region. A similar cycle of 20 to 22 yr was reported for the western USA (Mitchell et al. 1979).

Consistent with the recommendation of the WMO, few endeavors have discovered any rainfall periodicity in Israel. One which was informative was the work by J. Neumann and S. Kotz (cited in Katsnelson 1956), who demonstrated with 2 independent statistical techniques using Jerusalem and Haifa data that there is no periodicity in the interannual Israeli rainfall. The same results were obtained by Gabriel & Kesten (1963), who applied various statistical methods including Fisher's periodogram (up to 20 yr cycle).

Because of the sophistication of computerized methods and the development of new techniques of spectral analysis, there is renewed interest in analyzing periodicity (thus ignoring the UNESCO recommendation). Zangvil (1979) first applied the linear power spectral density to 108 yr of Jerusalem data, and found an insignificant cycle of 3.3 yr and sub-cycles of 6 and 2.15 yr. However, when he transformed the spectrum into natural logarithmic frequency, a significant (at 95% level) major cycle of 3 to 3.3 yr and a secondary cycle of 2.15 yr were detected. The same significant results were obtained when the spectral analysis was done separately on 2 sub-samples of the Jerusalem homotopic series. Yet, the 2 yr cycle was found only for the first period (1846 to 1900). Similar results were obtained for the Mediterranean Climate region of California, USA. Zangvil (1979) suggested some hypotheses to explain the 3 yr cycle, but in the literature 2 yr cycles are more common and are known as Quasi-Biennial Oscillations (QBO). The Israeli Meteorological Service utilizes the QBO parameter in the multiple regression model for its seasonal rainfall prediction.

A Box-Jenkins test of randomness, which is actually an opposite test for trend and cycles, was applied to Jerusalem and Miqwe-Israel data by Ascolai & Thieberger (1987). They found that these rainfall series are random, i.e. there is no trend or periodicity. Unlike Zangvil (1979), who applied the technique to the homotopic Jerusalem series, Ascolai & Thieberger (1987) did not use the standardized data, due to the small differences between these series (10 mm). They obliquely referred to the results of previous studies on the same topic, but unfortunately, did not refer to Zangvil (1979).

Spectral analysis was also applied to the spatial volume of rainfall (Stanhill & Rapaport 1988). It revealed 2.7 and 3.2 yr cycles and a secondary cycle of 13.5 yr. The results were found significant at 10% using 2 tests. In one of these the 2.7 yr cycle was found to be significant at the 5% level. But the authors nevertheless considered these findings not to be significant.

The existence of 2 and 3 yr cycles is supported by Beer-Sheva data. Orev (1986) found that above average rainfall years tend to appear consecutively, in pairs (20 out of 27 cases), with the third year being dry. However, multi-year dry periods of even 5 to 7 yr (22 out of 33 dry years) also occur. The distinction between 'wet' and 'dry' years in this context is easily made since few annual rainfall accumulations for this station (Beer-Sheva) are within 5% of the annual average (200 mm).

The Israeli experience in the search for climatic periodicity has not been impressive. The lack of significant findings is not merely the result of the UNESCO recommendation, but rather by the lack of a long homogeneous rainfall series. One cannot rely on only 1 or 2 long rainfall records in order to establish a significant periodicity. In South Africa, for example, where a periodicity was detected, 35 rainfall stations were established before 1880 and more than 150 by 1906 (Tyson 1986). Thus, the few studies reviewed here may be regarded as preliminary academic trials, while an intensive and serious study of this interesting topic will have to wait for a more extensive rainfall series.

LONG-TERM RAINFALL VARIABILITY

The historical rainfall record in Israel is relatively short. Except for Jerusalem, where rainfall has been recorded for nearly 150 yr, the veteran stations began to operate only during this century. Comparisons of all available rainfall normals were made by Elbashan (1965) for 1901–1930 versus 1931–1960; Goldreich & Manes (1979) and Goldreich (1987, 1988) for 1931–1960 versus 1951–1980 data; Goldreich (1990) for 1931–1960 versus 1961–1990 normals and Bitan-Buttenwiesser (1963) for 1901–1930 versus 1931–1960 for Tel-Aviv versus Jerusalem data. The rest of this section is devoted to the general rainfall trends and oscillations during the past 150 yr in Israel.

A comparison between Jerusalem rainfall and global sea surface temperature variations (Neumann 1986a) suggests 3 distinct climatological periods: a cool and rainy period between 1880 and 1912, followed by a warming trend up to the 1940s, then a cooling trend. The warm period was drier than the cooler ones. This negative correlation is similar to the relationship between temperature and rainfall on the interannual scale discussed earlier.

Neumann (1986b) also examined Miqwe-Israel rainfall versus temperature data and came to the same conclusion. Table 4 shows data from 3 rainfall periods at Miqwe-Israel. A somewhat different division of wet and dry periods is derived from a spatial rainfall volume study for the whole country by Stanhill & Rapaport (1988). It was found that in a sequence of 54 yr it is possible to find 2 relatively wet periods, 1934 to 1954 and 1965 to 1981, separated by a period of 10 dry years. From Table 4 it can also be deduced that the standard deviation of precipitation for the cooler period was greater than for the warm periods. This supports the notion (mentioned above) that cooler and wetter years are caused by penetration of cold air masses which increase the number of the rainy storms. Therefore, during the cooler period the cyclone storm variability causes the higher standard deviations of precipitation. This negative temperature-rainfall correlation is also found in the data at other temporal scales (daily scale, Gagin & Neumann 1974; monthly, Striem 1979; annual, Striem 1979).

Recent (1961 to 1990) rainfall trends point to a spatial nonuniformity (Steinberger & Gazit-Yaari 1992). In the northern Mediterranean climate region (Haifa and the Galilee) and in the greater Tel-Aviv area there is a trend of a decrease in rainfall, while the trend has been of increasing rainfall in the southern areas (including Qiryat- Anavim, 5 km west of Jerusalem). As yet, no convincing explanation has been given for this phenomenon.

The increase of October rainfall during the second half of this century in the southern part of the country (Goldreich 1990, Otterman et al. 1990) is not significant from the water management point of view. Yet, it may indicate that some climatic changes do occur. This increase in October rainfall, occurring as it does while the ground temperature is still high, may result in a land-use change in the south. This implies a decrease in the ground albedo and therefore an increase in the convective instability during the daytime hours. Increased instability could give rise to additional convection. This process is the reverse of the desertification postulated to occur in regions such as the Sahel (the southern fringe of the Sahara Desert) from over-grazing which increases the albedo (Otterman 1974, 1977) and may indicate an equatorial migration of several of the wind and pressure belts.

Some support for a reversed desertification process may be found in the decrease of the coefficient of variance in the Negev Coastal Plain, during 1963–1964 to 1984–1985 in comparison with the years 1938–1939 to 1962–1963 (Ben-Gai et al. 1994). They also claimed that in the second period the rainfall increased by 20%. However, a simple comparison of normals from 1931–1960 (IMS 1967) and 1961–1990 (IMS 1990), revealed a less dramatic change (a general increase of 0 to 3% in this region).

Table 4. Rainfall variations in Miqwe-Israel (Neumann 1986a)

Period	Rainfall (mm ± SD)
1915–1939	517 ± 141
1940–1969	550 ± 174
1970–1983	531 ± 127

CONCLUSION

Various scales of the temporal rainfall variation in Israel have been presented. The basic understanding of the different temporal scales was already achieved during the 1950s, mainly by J. Katsnelson, J. Neumann and N. Rosenan from the Israel Meteorological Service. The need for this essential information for many reasons, including the investigation of the behavior of rainfall variability, has encouraged the establishment of a meteorological data bank, increased the climatological weather stations and prompted compilation of relevant data under various departments of the Israel Meteorological Service.

There are several reasons for the increase in the number of studies devoted to these topics since the 1950s. New research and learning units exist in many institutions of higher education. Secondly, the period for meteorological records, which was previously too short, is now longer and therefore more suitable for analysis. The third reason is the development of faster computers and the application of easier and more sophisticated statistical techniques, such as spectral analysis. A fourth reason is the increase in the public awareness of environmental conservation and the global warming trend. It is also worth mentioning another reason: the involvement of climatologists in reconstructing past climates. Knowledge exchange between climatologists and paleoclimatologists is essential for understanding paleoclimatic variations with reference to present climatic variability. It is also true that insight into past climates can be a basis for the extrapolation of recent data for the purpose of projecting the most probable near-future climate scenarios.

Beyond the understanding of the past climate and predicting reasonable scenarios for future climate, a understanding of contemporary rainfall climate variation has further applications: e.g. reliable statistics on the regional probability of drought, understanding the behavior of rain spells, knowledge of the variability of rainfall intensities within rain spells and determining rainfall periodicity. The prediction of seasonal rainfall, still in its infancy, has already been linked to several climatic parameters based on local rainfall variations. A comprehensive summary and a critical review of these seasonal prediction techniques applied in Israel can be found in Mandel (1994a, b).

Regional cycles or quasi-cycles that have been detected had to be based on prolonged and reliable rainfall data for many stations. Unfortunately, due to the lack of such a group of stations, the determination of rainfall periodicity in Israel will have to wait. However, for other temporal rainfall parameters where the sample size of the data set is significant, re-examination of the longer and sometimes better quality data may help us to improve our understanding of the rainfall variability and to improve its applicative implications.

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