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ON THE URBAN OROGRAPHIC RAINFALL ANOMALY IN JERUSALEM—A NUMERICAL STUDY

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Abstract—A high-resolution meso-γ scale indexing of the orographic precipitation over the Judean Mountains in Israel suggests a positive urban precipitation anomaly in Jerusalem. The urban rainfall enhancement for three case studies is found to be 20–30 per cent as compared to only about 10% for the annual normals. The role of the urban 'heat island' and the larger supply of artificial nuclei is discussed. The method presented here is a primary attempt to separate quantitatively urban precipitation effects over highly complex terrain, by applying a physical model.

Key word index: Urban rainfall, orographic rainfall, mesoscale rainfall modelling.

1. INTRODUCTION

It has been noted for a long time that urban areas affect precipitation in their immediate vicinity. As early as 30 years ago, Landsberg (1956) stated that the amount of precipitation is about 10% higher in urban areas than in nearby rural regions. More comprehensive research (Oke, 1979; Landsberg, 1981) has shown that cities might cause an increase in precipitation for the following reasons.

(1) The well-known urban 'heat island' promotes air instability in urban areas.
(2) Absolute humidity is found to be somewhat higher in certain cities.
(3) Urban roughness enhances mechanical convection.
(4) The urban atmosphere contains large quantities of CCN (Cloud Condensation Nuclei) and IN (Ice Nuclei).

However, the urban effect on precipitation is very difficult to estimate for several reasons. First, only a few rural regions remain undisturbed from their natural states. Second, there is an insufficient number of raingauges in metropolitan areas, especially those with long-term records and uniform exposure throughout the measurement time. Third, many cities are associated with bodies of water or hilly terrain both of which can affect precipitation patterns on their own.

At an industrial downwind region near La Porte, Indiana, Changnon (1968) found a rainfall increase of 31%, for the period 1951–1965. He also found an increase in thunderstorms and hail days for this period. On the other hand, Spar and Ronberg (1968) found a somewhat decreasing trend in precipitation in the New York City area for the period 1927–1965. Eagleman *et al.* (1972) suggested the following explanation for this discrepancy. Large cities like New York supply large quantities of condensation nuclei to the urban atmosphere, thus reducing precipitation, while small cities supply adequate amounts of condensation nuclei, resulting in an increase of precipitation.

It seems, therefore, that the urban effect on precipitation depends on many factors, such as the regional climate, the particular mechanism of precipitation (convective showers, frontal or orographic precipitation, etc.) and the size and specific features of the urban area. Investigators have thus claimed different explanations for the cause of rainfall increase in urban areas. Khemani and Ramana-Murthy (1973), for example, related a rainfall increase downwind of the Bombay Industrial Complex to extensive industrial development. Atkinson (1975) in London and Goldreich and Manes (1979) in Tel Aviv associated urban precipitation increases with a mechanical 'heat island' effect. In the course of the most extensive urban climatic study, the METROMEX project (Changnon, 1979), the excess rainfall in and around the St. Louis urban area was carefully checked during a 5-year period of investigation. The rainfall increase, situated some 20–30 km downwind of the city, was related to a complex interaction among the following factors: wind, 'heat island', moisture and huge cloud condensation nuclei (Changnon *et al.*, 1976). It should be pointed out that St. Louis was chosen due to its relatively homogenous terrain, e.g. Pielke and Segal (1986), because of the difficulty in isolating the urban effect over highly complex topography. The problem of isolating the urban from topographical effects was extensively discussed by Goldreich (1984), but only few physical models attempted at solving it, e.g. Hjelmfelt (1982). To the best of our knowledge, none of these models considered the precipitation over complex urban topography.

In the present study we apply an orographic model (Alpert and Shafir, 1989a) to a hilly domain in central Israel. During the research we found that in the large urban area of Jerusalem the amount of rainfall is almost always higher than model prediction and in contrary to what happens at rural stations. This was found to be true at most of the city stations for yearly averages as well as in three case studies of rain events. Section 2 briefly explains the verification process, while section 3 is a discussion of the possible physical mechanisms causing an increase of precipitation in the hilly urban area of Jerusalem in the winter.

2. MODEL SIMULATIONS—URBAN AND RURAL RESULTS

The model used (Alpert and Shafir, 1989a) is basically an extension of an earlier orographic model by Alpert (1986) to a horizontal two-dimensional plane that follows hilly terrain. The study domain is a 30 $\times$ 60 km rectangle over the Judean Mountains located in central Israel (Fig. 1), and the grid interval is $\Delta x = \Delta y = 2$ km. The model was applied for annual averages as well as for three case studies, and the results were compared to raingauge observations and to climatological and radar derived precipitation. The case studies chosen were with relatively large amounts of orographic rain and where radar data were available; for more details see Shafir (1988). The model was also found useful in complementing rainfall normals over complex terrain, Alpert and Shafir (1989b). During the research it appeared that stations in the urban area of Jerusalem almost always got more rain than the model's prediction. When calculating the correlation coefficients with only the rural stations we have always found higher correlations than with all stations. Table 1 lists the correlation coefficients and the significant levels of the correlations with and without the city stations. Figures 2a and 2b are verification graphs of model predictions against raingauge observations with and without city stations, respectively, for 1931–1960 annual averages. The corresponding simulated and observed rainfall distributions are shown in Figs 3a and 3b, respectively.

Alpert and Shafir (1989a,b) discuss in some detail the differences between the simulated and observed distributions. Here, the attention is addressed to the bend in the isohyets 450–550 mm extending from the northwest to the southeast and to Jerusalem. This bend is found only in the observations (Fig. 3b) and not in the model prediction (Fig. 3a) and may be the outcome of an urban effect.

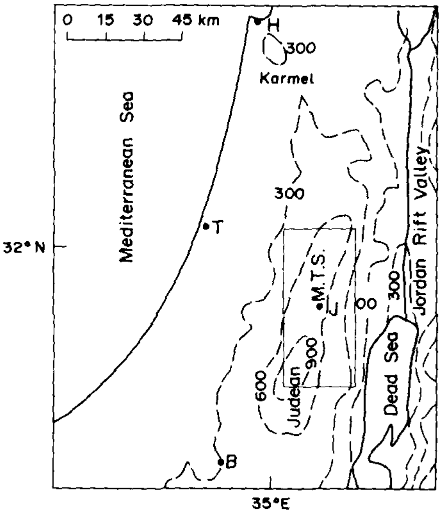

Fig. 1. General location of the study domain. Topographic contours with 300 m intervals. Rectangular area denotes the study domain. Letters H, T, J, B represent towns of Haifa, Tel Aviv, Jerusalem and Beer Sheva, respectively.

Figures 4a and 4b are verification graphs for the 4–5 March case study. The correlations are always higher when correlating with just the rural station. Notice especially the correlation of 0.56 at the 4–5 March 1983 event which improved to 0.8 without the city stations (Figs 4a and 4b). To further investigate the phenomenon we examined two groups of stations: inside and outside Jerusalem. The stations outside Jerusalem, serving as control stations, are at rural regions but not downwind to Jerusalem, and are located in about the same average altitude (± 20 m, see Appendix Tables A1–A10) as the city stations. The average location of the rural stations is 6–8 km west (upwind) to the city. Station's locations are plotted in Fig. 5 over a detailed topography; stations used in rain events are marked by a circle, while those used for annual averages are marked by a + sign. All available raingauges from the IMS (Israel Meteorological Service) were used. The normalized departures of the model predictions from the observations as averaged for both the urban and rural groups of stations separately is presented in Table 2. Results are shown in per cent for the annual averages and for the three case studies. Modelled and observed rainfall values along with additional information for all stations are given in Tables A1–A10 in Appendix 1. In general it was found that stations inside Jerusalem get more rain than model predictions, while at rural stations model predictions fit the observations. The main conclusions follow.

(1) The urban enhancement during rain events at Jerusalem is about 20%. In the late winter event of 4–5 March 1983 it increases to 31%. The results are significant at more than 99%.
(2) In the annual averages the urban enhancement is about 10%.
(3) The urban increases were found somewhat higher in downwind urban stations (see Appendix 1, stations St. Anna and Jerusalem Center).
(4) The urban enhancement in recent years (1951–1980) is about the same (9 compared to 10%) as in the past (1931–1960). The urban increase of 2.3% in the later period was cancelled out by a similar growth at the rural stations of 3.3% to result in a slight decrease of 1% in the total urban enhancement.

It should be pointed out that the urban enhancements of 10% and 20–31% for annual case and events, respectively, are of a similar magnitude to the model error ($\pm 8.4\%$ and ± 15–20%, see Alpert and Shafir, 1989a). However, the model 'errors' in the urban stations are always with the same sign and in general with the opposite sign for the rural stations.

The statistical tests that were performed are for the decision between two hypotheses. The null hypothesis is HO: $M1 = M2$ while the examined hypothesis is H1: $M1 > M2$, where M1 and M2 are the observed and modelled rainfall means. The T-test determines whether H1 hypothesis could be accepted.

Table 1. The five model experiments and the correlation coefficients between the observed and modelled rainfalls. Numbers in parentheses present the number of stations in the pertinent correlation. The two right columns list the corresponding figure numbers and the table numbers with the relevant data

Experiment	All observations	Rural observations	Table numbers (Appendix)	Figure number
1. Annual 1931–1960	0.74* (56)	0.76* (41)	1.1–1.2	2a, 2b
2. Annual 1951–1980	0.73* (37)	0.76* (29)	1.3–1.4	—
3. First case study 16–21 February 1983	0.62* (29)	0.70* (23)	1.5–1.6	—
4. Second case study 31 December 1982–2 January 1983	0.38† (32)	0.45* (26)	1.7–1.8	—
5. Third case study 4–5 March 1983	0.56* (31)	0.80* (25)	1.9–1.10	3a, 3b

* Significant at 99%.
† Significant at 95%.

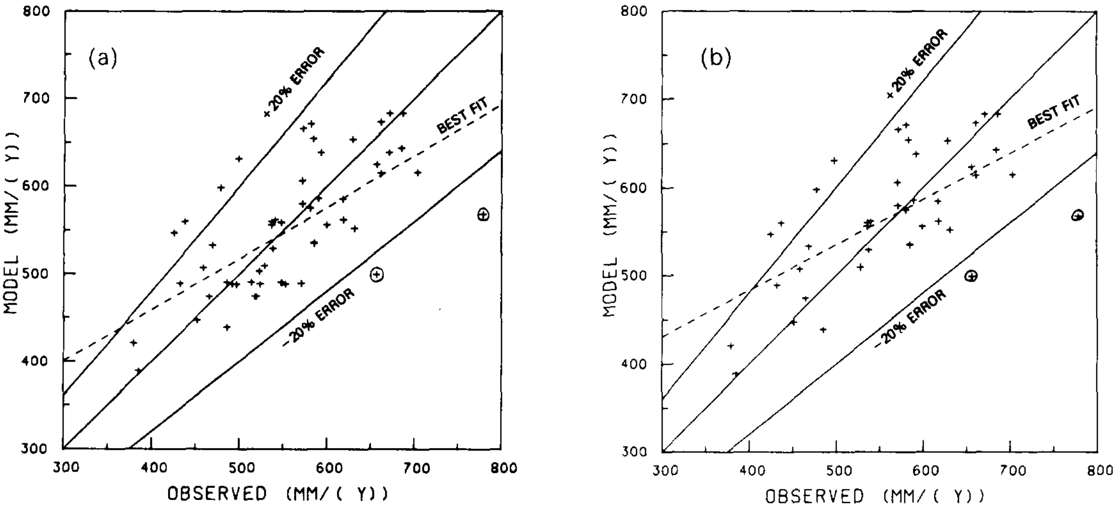

Fig. 2. Distribution and a regression line (best fit) for model and observed annual rainfall normals for 1931–1960 (a) with all observations; (b) with the observations excluding the urban (Jerusalem) stations. Correlation coefficients are 0.74, 0.76, respectively, see also Table 1. Lines of ±20% error are also shown. The two encircled crosses were suspected to be erroneous (Alpert and Shafir, 1989a).

3. DISCUSSION

3.1. *The urban effect and the orographic rain mechanism*

Although it is very difficult to determine the relative importance of the different urban factors causing increases in precipitation, the extensive urban studies (Changnon, 1970; Changnon *et al.*, 1976) pointed out that the two main reasons for urban precipitation increases are the 'heat island' effect and the large quantities of CCN inside cities. In order to estimate the 'heat island', statistics of surface temperature inside and outside Jerusalem during the three rain events was conducted. It was found that the average urban temperature was higher in all cases varying from 0.83°C on the 4–5 March event to 0.35°C and 0.17°C in the other events. The relatively high observed 'heat island' on the 4–5 March corresponds with the maximum urban enhancement, Table 2. The value of 0.83°C is close to 0.58°C predicted by Karl *et al.* (1988) formula for a 400,000 city population during winter.

The effect of such an 'heat island' on vertical veolcity and precipitation was estimated by the use of theoretically calculated vertical winds due to sea breezes over circular islands, Neumann and Mahrer (1974). In their study they found that a surface temperature gradient of 0.75°C/1 km induces maximum vertical winds of about 50 $cm\,s^{-1}$ over a region of about 10 km. Hence, here the corresponding vertical velocity over the Jerusalem 'heat island' of 0.83°C will be $\sim 8\ cm\,s^{-1}$. This value should be compared to $\sim 3\ cm\,s^{-1}$ needed for the corresponding rainfall en-

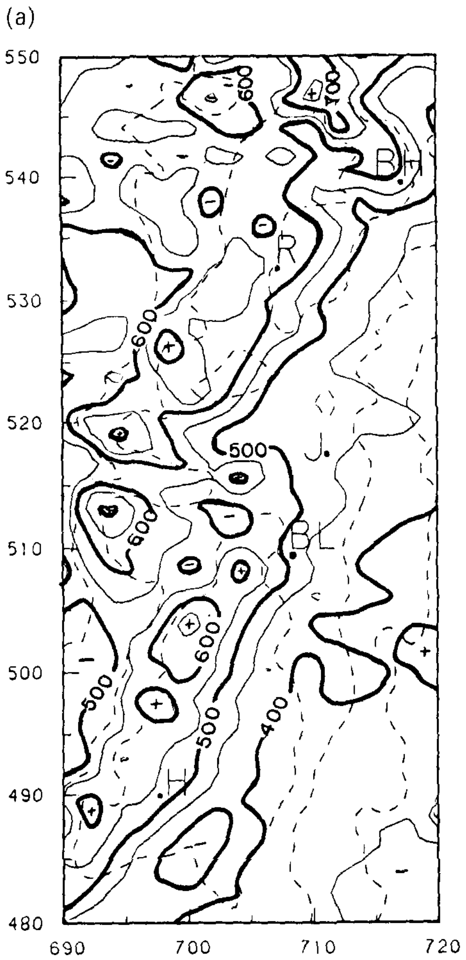

Fig. 3a. The annual isohyets (in 50 mm interval) from the model simulation are drawn. Dashed lines are the topographic contours with an interval of 200 m. Grid numbers are in kilometers. The letters BH, R, J, BL and H denote the locations Baal-Hatsor, Ramalla, Jerusalem, Bet-Lehem and Hevron, respectively.

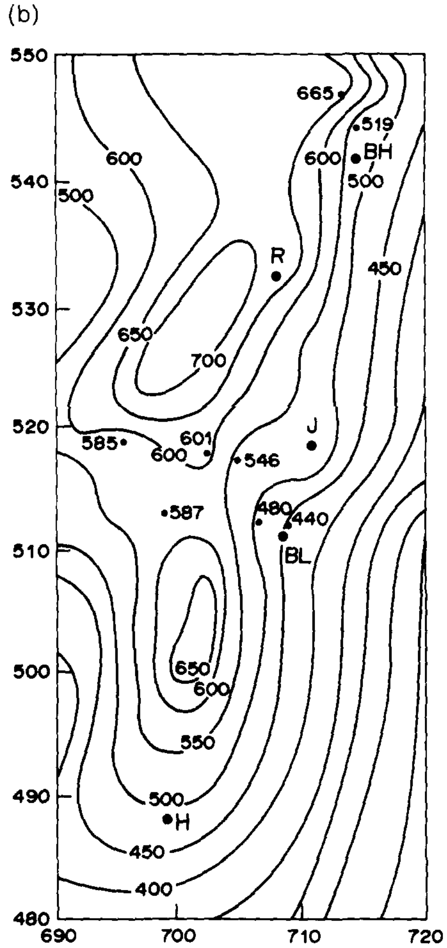

Fig. 3b. Observed contours of average annual rainfall based on data from about 58 gauges during the period 1951–1980. Rectangle designates the pertinent region from Fig. 1 and was taken from an IHS (Israel Hydrological Service) map. Contour interval is 50 mm y^{-1}. The observed rainfall normals at some stations are also indicated.

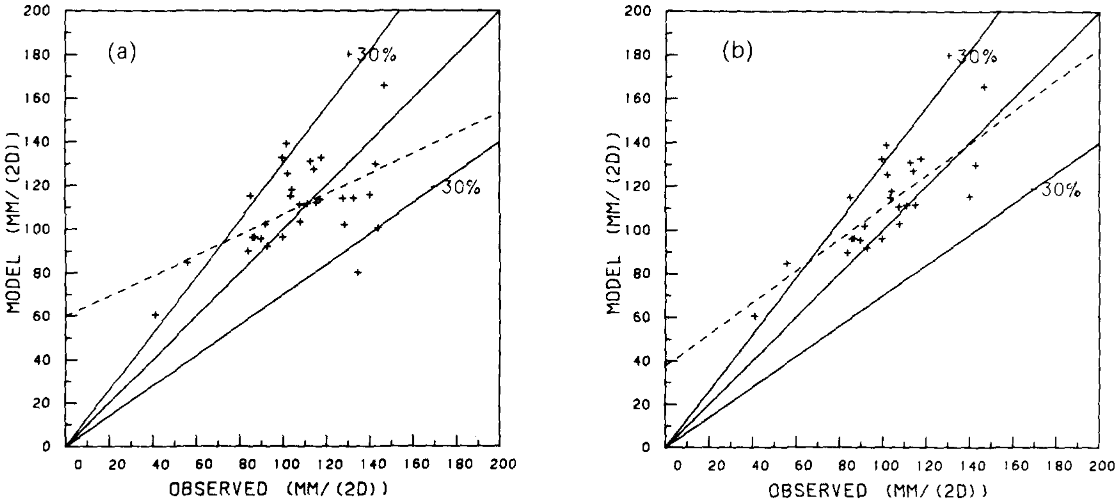

Fig. 4 a,b. As in Fig. 2 a,b but for the 4–5 March case-study and with $\pm 30\%$ error lines.

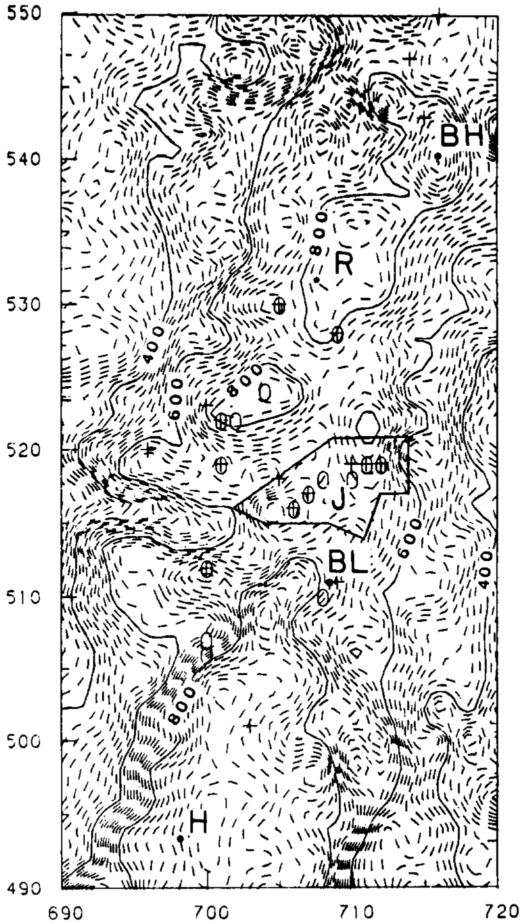

Fig. 5. High resolution topography (dashed) of the study domain with a contour interval of 20 m. The 400, 600 and 800 m contours are drawn as solid lines. Circled stations designate locations for the case studies while a 'plus' sign stand for stations in the annual study. The urban region of Jerusalem is surrounded by the solid line in the center.

hancement of 27 mm, see Table 1.9 and formula (2) in Alpert and Shafir (1989a). Similar 'urban vertical velocities' were also found in a three-dimensional numerical model investigation in St. Louis by Hjelmfelt (1982).

The second possible factor in urban precipitation is the increased amount of CCN in the city's atmosphere. Kellog *et al.* (1972) and others have shown that man-made SO_2 and NO_x emitted to the atmosphere can be effective as CCN, the quantity of which is equal to the amounts of naturally produced CCN inside cities. It has been shown by Graber (1980–1983) and Luria *et al.* (1984b) that Jerusalem has been polluted with SO_2 and NO_x.

Up to now, we have discussed the relative importance of two main causes ('heat island' and CCN) which can increase precipitation. However, in most urban research, the physical processes causing urban precipitation increases are much more complicated, involving interactions of meteorological conditions with various urban factors. In the METROMEX project, for example, it was found that the combination of a 'heat island' effect and giant CCN defined a plume which was advected by the wind some 20–30 km downwind where it caused an increase in rainfall (Changnon *et al.*, 1976; Shea and Auer, 1978). In contrast to St. Louis which is situated over gentle terrain, Jerusalem is located on hilly topography where the most frequent type of precipitation is orographic.

One orographic precipitation theory, suggested by Bergeron (1965) and put forward by Browning (1980), claims that the orographic enhancement is due to orographic feeder clouds formed as a result of the interaction of moist low-level winds with mountain slopes. These clouds, located near mountain surfaces, contain warm drops which are efficiently washed out by drops falling from higher cold seeder clouds formed by synoptic processes. The warm feeder cloud is thus highly dependent on CCN concentrations in the atmosphere. A possible explanation for urban orographic enhancement, therefore, may be due to the urban area continuous supply of CCN into the feeder orographic clouds. These particles are efficiently convected upwards also due to the 'heat island' effect and keep the CCN level from decreasing. This seems to work especially when the amount of natural CCN decreases, as is the case for most rain events in

Table 2. Averaged departures (in per cent) of rainfall predictions from the observations for the urban and rural groups of Jerusalem stations both for the annual averages and the three cases studies. The right column presents the urban enhancement

Experiment	Urban stations (%)	Rural stations (%)	Urban enhancement (%)
Annual 1931–1960	+6.9** (6)	−3.1*** (12)	+10
Annual 1951–1980	+9.2** (6)	+0.2*** (12)	+9
16–21 February 1983	+20.9* (6)	+0.9*** (8)	+20
31 December 1982–2 January 1983	+16.0** (6)	−4.0*** (9)	+20
4–5 March 1983	+26* (6)	−5.6*** (10)	+31.6

* Significant at 99%.
** Significant at 95%.
*** Not significant (less than significance of 80%).

Jerusalem, Israel, as reported by Terliuk and Gagin (1971). A support for this process could be found in the fact that the urban orographic anomaly seem to be enhanced in the case where both the orographic (Alpert and Shafir, 1989a) and low-level humidity are the highest, i.e. the 4–5 March event. In this event we found an average relative humidity of 96% at 900 mb (99% at 850 mb) compared to 84% and 88% in the other events (85 and 91% at 850 mb).

Another question relates to the location of maximum enhancement: in some studies, i.e. METROMEX, Goldreich (1987), the urban increase was found to be greater some distance downwind of the main urban area. Here, the urban precipitation increases are found already inside the town and slightly downwind. But, there are no rainfall stations outside the city downwind which could verify such an increase. A possible explanation to the rainfall increase inside the city in this case is that the orographic feeder clouds are washed out quite fast as they form over a mountainous region and are *not* advected efficiently as happens in the flat area of St. Louis.

The reason for the high urban intensification particularly during the cold and late rain events is explained as follows. First, as already discussed, there seems to be a link between enhanced orography and urban effects. The enhanced orographical effect in late winter was discussed by Druyan *et al.* (1986) who referred to the same area of the Judean Mountains. Second, there is a higher emission of CCN as a result of the increased domestic heating. Also, the artificial heating may cause an enhanced 'heat island' effect, which, in turn will lead to greater instabilities and enhanced precipitation.

3.2. *The urban anomaly in* 1951–1980 *vs* 1931–1960

Another question relates to the insignificant urban change in the last 30 years 1951–1980 compared with the years 1931–1960, even though the urban area of Jerusalem has been considerably expanded. The population in Jerusalem increased from ~80,000 in 1948 to about 280,000 inhabitants in 1969, see Fig. 6 from the Hebrew Encyclopedia (1971) and Luria *et al.* (1984b). The precipitation increase of 2.3% (not significant) during the last 30 years was balanced by a similar growth at the rural stations. The recent growth both in urban and rural stations could be the result of the cloud seeding in recent years (Gagin and Neumann, 1974) or of the increase in CCN particles advected from Israel's major industrial coastal plain to the mountainous regions (Luria *et al.*, 1984a). The two mechanisms affect similarly both the urban and rural region.

The recent climatic change in Jerusalem could also be noticed in the relation between the rainfall and temperature long-term time series in Jerusalem for 1860–1970. Figure 7, from Striem (1985), shows that mean decadal values of the rainfall are strongly negatively-correlated with temperature. Striem (1979) has even indicated that ~100 mm of annual rainfall in-

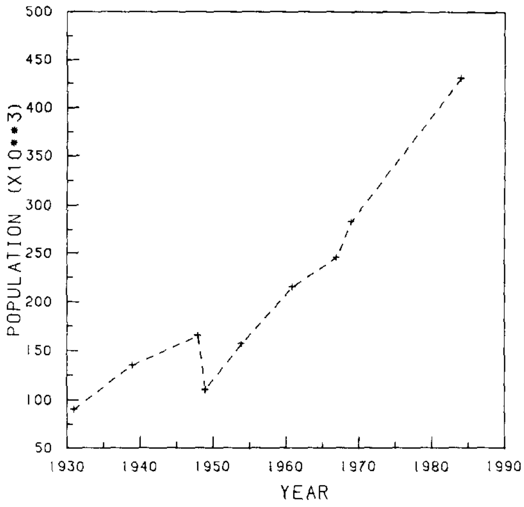

Fig. 6. Jerusalem number of inhabitants for the period 1931–1984. From the Hebrew Encyclopedia (1971). The 1984 value is from Luria *et al.* (1984b).

crease is associated with a 1°C decrease and *vice versa*. This rule is good only up to the 1950s but since that time the rainfall increase is clearly *not* associated with a corresponding temperature decrease. The temperature is kept at about a constant value of 11°C which is ~1°C warmer than in the preceding century. Actually, Striem (1974) himself when indicating the recent climatic rise in Jerusalem winter temperatures (1.5–2°C) as opposed to the steady summer temperature has suggested that this might be attributed to the increasing urbanization of Jerusalem. Such a climatic change is clearly consistent with major urban development which took place in Jerusalem since the 1940s (Fig. 6). The rainfall increase could be associated with the various urban mechanisms as discussed earlier and the temperature does not decrease due to the increased 'heat island' effect.

3.3. *Is it really an urban anomaly?!*

In the following section other possible sources for the urban enhancement in our results will be discussed.

3.3.1. *Effect of dynamic circulations that have not been incorporated in the model.* The model is highly simplified since it assumes that the distribution of orographic rain is determined primarily by the adiabatic geometrical uplifting by the mountain slope. Non-linear dynamical interactions or even linear disturbances like gravity waves or lee cyclogenesis are assumed to be only secondary and this was basically the suggestion made by Alpert and Shafir (1989a). Although the Jerusalem stations seem to be closer to the exit of the west–east Sorek Valley (Fig. 5, approximately along the ordinate of 515–516) which could result in a more effective channelling of the westerly winds, there are some rural stations as well which have a similar geographic position, e.g. Alon Shvut and Rosh Zurim at (506,700). The latter stations as well as

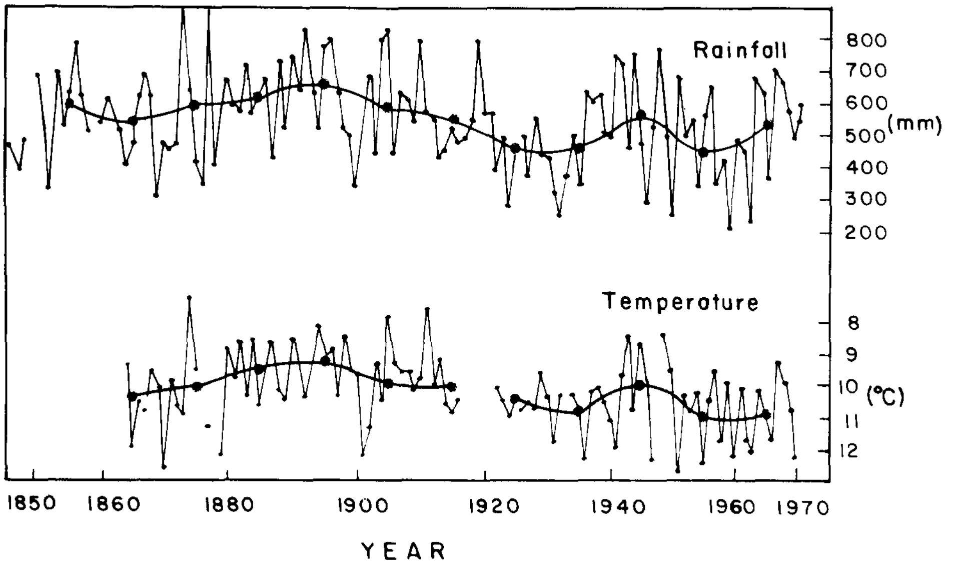

Fig. 7. The chronological sequence of winter rainfall and temperature in Jerusalem during 1860–1970. Circles denote mean decadal values. From Striem (1985).

all other rural stations—except Zova at (519,701)—are consistent in reporting less rainfall than in the model. A full verification of the aforementioned assumption will have to await sophisticated three-dimensional model rainfall simulations in the meso-γ scale which are not yet available with satisfactory results. For a comparison of the current model with sophisticated model simulations see Alpert (1986).

3.3.2. *Effect of the different geographical location of rural vs urban stations.* It is well known that rainfall normals in Israel tend to increase towards the north, towards the west (closer to the Mediterranean Sea) and at higher elevations. Diskin and Davis (1970) have proposed a statistical regression equation for rainfall normals in Israel which calculates the abovementioned dependencies as function of latitude, longitude and elevation at any point. The average location of the rural stations is displaced slightly to the northwest and at a higher elevation. Hence, the average amount of precipitation should be higher in the rural stations. According to Diskin's formula this difference is of about 27 mm. This is an underestimation of the observed differences of 53 or 62 mm in 1930–1960 and 1950–1980, respectively (Tables A1–A4). It is not unexpected that the statistical equation errors are very large on smaller-scale regions since the regression equations were derived for the whole region of Israel (Wolfson, 1975). This difficulty of the statistical model, however, stands in contrast to the physical model which predicts a large difference of 106 mm between the rural and the urban stations (Tables A1–A2). Since the urban anomaly results from differences between the model prediction and the observations and both are supposed to contain the effect of the geographical shift this cannot affect the calculated urban to rural anomaly.

3.3.3. *Effect of the efficiency factor in the model.* The preceding section returns our attention to the model and to its parameterization. As indicated by Alpert and Shafir (1989a) the rainfall equation contains an efficiency factor ρ which although being changed from case to case in order to equate the average simulated rainfall to that observed is kept constant in the same case. That means that any variation in ρ cannot change the relative urban to rural pattern and will only be reflected in small percentage variations due to changes in the total amounts of rainfall.

4. SUMMARY AND CONCLUSIONS

The evidence presented here supports a positive urban precipitation anomaly in Jerusalem. Urban orographic precipitation increases are very difficult to estimate since such urban areas are associated with complex terrain and it is very difficult to distinguish between the urbanic and orographic contributions. Therefore, the tested orographic model (Alpert and Shafir, 1989a) is suggested in the present work as an efficient tool to separate between the two components and to enable us to estimate the urban enhancement in orographic areas.

In general it appears that urban orographic increases are high. A possible explanation of this is the supply of great amounts of CCN to the orographic feeder clouds which are strongly dependent on it. For cold rain events the urban contribution may even be greater as a result of the higher artificial energy used which, in turn, causes greater CCN emissions and an enhanced 'heat island' effect.

In order to further investigate the phenomenon presented here, we must not only use such models in other orographic urban regions, but also employ techniques for sampling the raindrops. In addition, three-dimensional microphysical orographic models must be used in order to realistically simulate the microphysical effects including the CCN contribution to precipitation in orographic urban areas. A major step towards this goal have been only recently performed by running the three-dimensional PSU/-NCAR model in the meso-β scale (down to a grid distance of 2.5 km) for the METROMEX data, Seaman *et al.* (1989).

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APPENDIX 1: URBAN AND RURAL TABLES

Tables A1 and A2 are for 1931–1960 averages inside and outside Jerusalem, respectively. Tables A3 and A4 are for 1951–1980 averages, and Tables A5–A10 are for the three case studies.

Table A1. Urban stations—1931–1960 averages

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	St. Anna	740	519	712	520	469	+51
2.	Jerusalem center	810	519	711	486	479	+7
3.	Old City	760	519	710	492	488	+4
4.	Ein Karem	660	518	705	548	485	+63
5.	Beit Vagan	810	517	707	548	514	+34
6.	Manhat	760	516	707	576	531	+45
Average		757	518	708.7	528.3	494.3	34 = 6.9%

Table A2. Rural stations—1931–1960 averages

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	Kariut	790	550	716	481	638	−157
2.	Sanjil	775	547	714	629	626	+3
3.	Mazra Sharkia	835	543	715	479	625	−146
4.	Beitunia	810	530	705	572	647	−75
5.	Atarot	740	528	709	572	556	+16
6.	Maale Hakhamisha	810	523	700	672	675	−3
7.	Kiryat Anavim	700	522	701	687	661	+26
8.	Shoresh	680	520	696	573	667	−94
9.	Zova	730	519	701	619	538	+81
10.	Mvo Beitar	760	512	699	537	576	−39
11.	Bet Lehem	760	511	709	529	473	+56
12.	Ein el Arub	830	501	703	632	522	+110
Average		768	525.5	705.7	581.8	600.3	−18.5 = −3.1%

Table A3. Urban stations—1951–1980 averages

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	St. Anna	740	519	712	505	469	+36
2.	Jerusalem Center	810	519	711	525	479	+46
3.	Old City	760	519	710	518	488	+30
4.	Ein Karem	660	518	705	565	485	+80
5.	Beit Vagan	810	517	707	580	514	+66
6.	Manhat	760	516	707	545	531	+14
Average		757	518	708.7	539.7	494.3	45.3 = 9.2%

Table A4. Rural stations—1951–1980 averages

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	Kariut	790	550	716	540	638	−98
2.	Sanjil	775	547	714	625	626	−1
3.	Mazra Sharkia	835	543	715	560	625	−65
4.	Beitunia	810	530	705	615	647	−32
5.	Atarot	740	528	709	568	556	+12
6.	Maale Hakhamisha	810	523	700	725	675	+50
7.	Kiryat Anavim	700	522	701	693	661	+32
8.	Shoresh	680	520	696	599	667	−68
9.	Zova	730	519	701	640	538	+102
10.	Mvo Beitar	760	512	699	589	576	+13
11.	Bet Lehem	760	511	709	450	473	−23
12.	Ein el Arub	830	501	703	616	522	+94
Average		768	525.5	705.7	601.7	600.3	1.3 = 0.2%

Table A5. Urban stations—16.2.83–21.2.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	St. Anna	740	519	712	158.0	104.2	+53.8
2.	Jerusalem Center	810	519	711	143.0	111.3	+31.7
3.	Tara Santa	735	518	710	143.5	111.3	+32.2
4.	University	700	518	708	140.5	114.4	+26.1
5.	Beit Vagan	810	517	707	146.5	145.0	+1.5
6.	Manhat	755	516	706	153.0	145.0	+8.0
Average		758	517.8	709	147.4	121.9	25.5 = 20.9%

Table A6. Rural stations—16.2.83–21.2.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	Beitunia	810	530	705	190	194.4	−4.4
2.	Atarot	740	528	709	186	144.1	+41.9
3.	Beit Nkofa	820	522	702	169.5	171.6	−2.1
4.	Kiryat Anavim	700	522	701	195.5	198.5	−3.0
5.	Zova	730	519	701	166.5	144.6	+21.9
6.	Mvo Beitar	760	512	700	160.0	144.4	+15.6
7.	Beit Gala	775	510	708	119.0	114.6	+4.4
8.	Alon Shvut	755	506	700	106.0	169.7	−63.7
Average		761	518.6	703.3	161.6	160.2	1.4 = 0.9%

Table A7. Urban stations—31.12.82–2.1.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	St. Anna	740	519	712	67.0	45.1	+21.9
2.	Jerusalem Center	810	519	711	61.0	47.8	+13.2
3.	Tara Santa	735	518	710	59.5	47.8	+11.7
4.	University	700	518	708	54.5	47.7	+6.8
5.	Beit Vagan	810	517	707	53.0	59.7	−6.7
6.	Manhat	755	516	706	62.0	59.7	+2.3
Average		758	517.8	709	59.5	51.3	8.2 = 16.0%

Table A8. Rural stations—31.12.82–2.1.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	Beitunia	810	530	705	61.5	76.3	−14.8
2.	Atarot	740	528	709	62.5	59.4	+3.1
3.	Bidu	850	524	704	66.0	61.5	+4.5
4.	Beit Nkofa	820	522	702	66.5	69.2	−2.7
5.	Kiryat Anavim	700	522	701	76.0	77.6	−1.6
6.	Zova	730	519	701	69.0	57.6	+11.4
7.	Beit Gala	775	510	708	64.0	45.5	+18.5
8.	Alon Shvut	755	506	700	43.0	67.5	−24.5
9.	Rosh Zurim	755	506	700	50.0	67.5	−17.5
Average		771	518.6	703.3	62.1	64.7	− 2.6 = −4.0%

Table A9. Urban stations—4.3.83–5.3.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	St. Anna	740	519	712	134.5	80.1	+54.4
2.	Jerusalem Center	810	519	711	144.0	100.5	+43.5
3.	Tara Santa	735	518	710	128.5	102.0	+26.5
4.	University	700	518	708	117.5	113.3	+4.2
5.	Beit Vagan	810	517	707	133.0	113.9	+19.1
6.	Manhat	755	516	706	128.0	113.9	+14.1
Average		758	517.8	709	130.9	103.9	27.0 = 26.0%

Table A10. Rural stations—4.3.83–5.3.83

No.	Station	Height (m)	Latitude (km)	Longitude (km)	Observed (mm)	Model (mm)	Difference (mm)
1.	Beitunia	810	530	705	108.0	103.0	+5.0
2.	Atarot	740	528	709	111.5	111.4	+0.1
3.	Bidu	850	524	704	100.0	132.5	−32.5
4.	Beit Nkofa	820	522	702	118.0	132.6	−14.6
5.	Kiryat Anavim	700	522	701	147.0	165.5	−18.5
6.	Zova	730	519	701	140.5	115.4	+25.1
7.	Mvo Beitar	760	512	700	85.5	114.8	−29.3
8.	Beit Gala	755	510	708	115.5	111.7	+3.8
9.	Alon Shvut	755	506	700	100.0	96.2	+3.8
10.	Rosh Zurim	755	506	700	87.0	96.2	−9.2
Average		769	517.9	703	111.3	117.9	−6.6 = −5.6%