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Temporal rainfall fluctuations in Israel and their possible link to urban and air pollution effects

Noam Halfon[1,2], Zev Levin[2] and Pinhas Alpert[2]

[1] The Porter School of Environmental Studies, Tel Aviv University, 69978, Israel
[2] The Sackler Faculty of Exact Sciences, Department of Geophysics and Planetary Science, Tel Aviv University, 69978, Israel

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Abstract

In this paper we analyze spatial variations of the annual rainfall that have taken place in the non-arid regions of Israel (annual rainfall > 200 mm) during the years 1952–2006, incorporating all available data. The results of the present study over the research area as a whole indicate that no significant temporal change of the annual rainfall occurred in any region of the study area. However, focusing on spatial rainfall fluctuations between sub-regions in the study area, a significant increase was observed between the stations located downwind and those upwind of the Greater Tel Aviv region.

This increase supports previous reports showing that rainfall enhancement is observed downwind (and close) to urban centers. In contrast to a few previous reports, no decrease in the ratio between the mountain precipitation to that over the coastal region was found. Over the period of the present study, the rainfall ratio between the upwind slopes and the seashore remained unchanged, with a slight increase in the central part of the country.

The only hilly place where a slight decrease in annual rainfall was observed is the lee side (eastern slopes) of the Galilee Mountains. This result is important because the eastern slopes of the Galilee Mountains have for years been part of the target area for Israeli artificial cloud seeding for rain enhancement. The results therefore suggest that unless there was a pronounced change in the synoptic conditions during rain spells, seeding in Israel had no positive effect on rainfall amounts.

Keywords: urban, rainfall, air pollution, aerosols, Israel

1. Introduction

The effects of aerosols on clouds have been widely studied. It is clear that increased aerosol concentrations, especially those that serve as cloud condensation nuclei (CCN) lead to smaller and higher concentrations of cloud drops. In warm clouds these effects slow down the development of precipitation due to the slower growth of hydrometeors by collection. The effects on clouds that contain both water drops and ice (mixed-phase clouds) are not yet clear, although there are observations and modeling studies suggesting that ice formation would occur higher up in the clouds, leading to higher or lower precipitation depending on the environmental conditions and on the interaction with the surrounding environment.

Measurements downwind of sugarcane fires first suggested a suppression of precipitation (Warner and Twomey 1967, Warner 1968) that was thought to be associated with the reduced efficiency of precipitation development due to an increase in CCN from the fires. However, Warner (1971) could not rule out the possibility that the decrease in rainfall was caused by changes in meteorological conditions. Hobbs *et al* (1970), on the other hand, observed increases in precipitation downwind of paper mills in Washington State. Although the presence of giant CCN was thought to be responsible for the observed increases, Hindman *et al* (1977) concluded that giant

CCN by themselves could not fully account for the observations and that other factors related to the environmental meteorological parameters are the dominant factors.

Analyses of precipitation downwind of urban areas carried out in the USA (Changnon *et al* 1976, 1977, 1981, Hjemfelt 1982, Huff 1977) showed increases in precipitation over the years especially in the summer season when rain is more convective. All the studies attributed these increases to urban effects, such as the urban heat island as well as changes in soil moisture and in roughness parameters affecting wind speed and convergence. More recent papers reached similar conclusions (Thielen *et al* 2000, Shepherd *et al* 2002, Shepherd and Burian 2003).

Most of the rain in Israel occurs in the winter due to the passage of cold fronts from the west. In addition, rainstorms from the Red Sea Trough sometimes bring local heavy rains, but their contribution to the total water budget of the region is small (Goldreich *et al* 2004).

Investigations conducted in Israel over the past few decades observed increases in precipitation in winter storms downwind of the two major urban areas in the country, Tel Aviv in the center of the country and Haifa in the north (Goldreich 1981, 1990, 1995, 2003, Goldreich and Manes 1979, Goldreich and Kaner 1991). Shafir and Alpert (1990) showed positive urban effects on rainfall over Jerusalem. Goldreich (1995) stated that although the statistical significance of each of these findings was not so high, the fact that all the reports reached similar conclusions using different techniques is a good indication that urbanization plays a role in the enhancement of rainfall downwind.

A hypothesis that a negative correlation exists between pollution levels and amounts of orographic precipitation due to the microphysical effects of aerosols on clouds has recently been proposed by Givati and Rosenfeld (2004, 2005, 2007). In these reports similarities were found between the suppression of orographic precipitation in winter storms in California and Israel. The results are based on temporal trends of the annual ratio, *Ro*, between mountainous stations and stations upwind (west) of the mountain. These findings are not supported by previous findings in Israel that showed only changes in the gradient of precipitation between the north and the south of the country (Ben-Gai *et al* 1994, 1998, Steinberger and Gazit-Yaari 1996, Zangvil *et al* 2003, Krichak *et al* 2002). Alpert *et al* (2008), utilizing the same method of orographic ratio analysis used by Givati and Rosenfeld (2004, 2005), but with more representative stations, found no real changes in the ratio between the amounts of annual rainfall in the mountains and at the seashore.

In the light of these conflicting results, it was decided to conduct a comprehensive climatological investigation of the rainfall, making use of *all* the available data in the study area (∼500 rainfall measurements per year), including some newly available data from over 50 stations in the West Bank. In this way, one can objectively evaluate the temporal changes in precipitation in Israel, with a special emphasis on the effects of the upwind urban regions on the rainfall downwind in the plains and the mountains.

2. Methods

Because of the inhomogeneous distribution of rain gauge stations in the study area, we analyzed the data and compared the results using four different methods: (1) a geographical information system (GIS) for computing annual rainfall maps, (2) a multivariable regression method, (3) computation of the mean regional measured rainfall, (4) temporal rainfall ratio trends between individual stations. These methods permit the use of all the available data from the studied period and thus avoid dealing with the question of which rain gauge stations better represent the studied area. It should be emphasized that in order to be as objective as possible, rain gauge stations with incomplete data records were not modified and were not completed (filled in) with data from neighboring stations.

2.1. Method 1—GIS computed annual rainfall maps

In this method we mapped all the available annual precipitation data in the non-arid regions of Israel (i.e. central and northern areas) and compared the amount of rain over the mountains with that over the seashore (see the detailed procedure in figure 1).

The analysis period was chosen to be from 1952 to 2006 (54 years) because it corresponds to a period in which data from a high density of rain gauge stations are available. This means that the procedure outlined in figure 1, mapping and computing annual means, was repeated 54 times, separately for each year.

More than 25 000 annual rainfall values were mapped (about 500 per year) over an area of 14 000 km^2 (see the research area in figure 2), a high density of about 1 station/30 km^2. The data were received from the Israeli Meteorological Service which routinely maintains and calibrates the rain gauges. Almost all the data were measured by standard gauges which have an accuracy of 1–2%. A few per cent of the measurements were done by 'tipping bucket' rain gauges which have an accuracy of 7%.

In order to improve the accuracy of the maps we define two parameters: (1) the mean annual rainfall, which reflects the effects of station elevations, latitudes and distances from the seashore on the amount of rainfall and (2) the actual amount of rainfall in each station in a specific year, which reflects the interaction between the geographical position of the stations and the synoptic conditions during specific rainy spells. Dividing the actual amounts of rainfall by the long term averages allows us to neutralize the average influence of geography on precipitation and to interpolate only the spatially random deviations from the mean. Another advantage of mapping relative amounts (actual amounts divided by the mean annual rainfall) is that the spatial mean of the mapped region is not strongly affected by occasional changes in the distribution of rain gauges in the study area.

The definition of the areas that were compared to each other was based on the topography (see figure 2(a)) and the wind direction during rainy spells (figure 2(b)). The mountain region in the north of Israel included all the areas above an

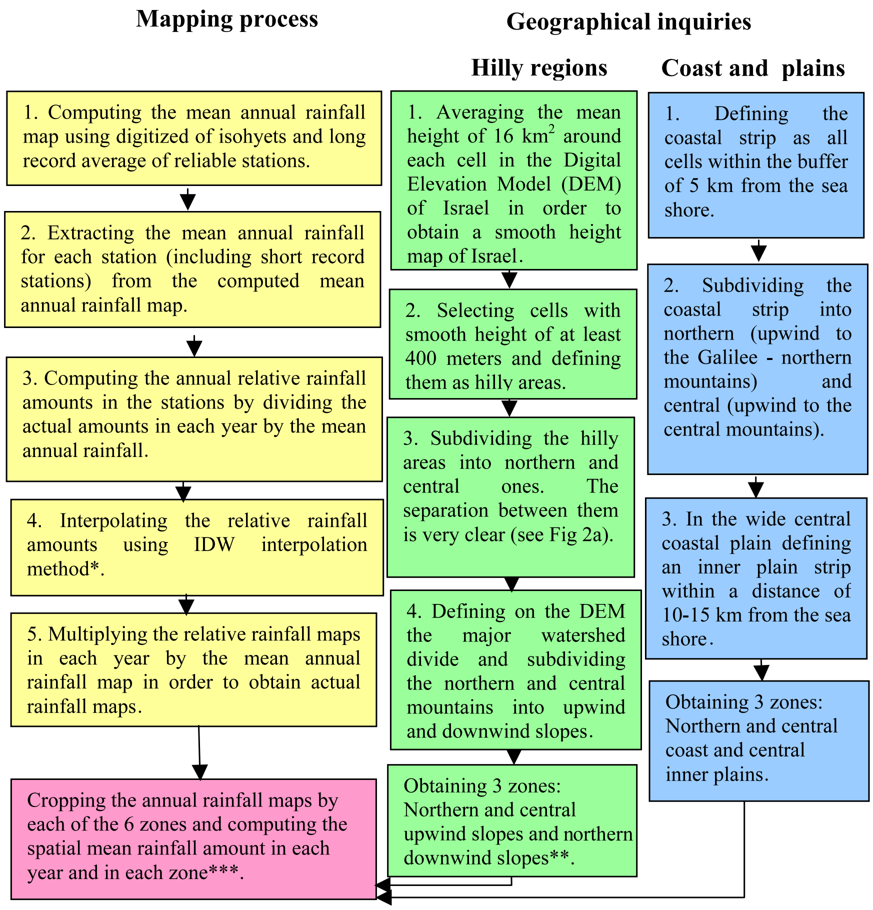

Figure 1. Flowchart of the mapping procedure and the computing process of the annual mean precipitation for each of the six zones of interest. * The weight of the inverse distance weighted (IDW) interpolation method was defined objectively by the 'Geostatistical Analyst' tool (ESRI 2004) according to the spatial distribution of the stations and their values in each year. The number of neighbors to include in the interpolation was set at 10. ** The central downwind slope region was not used in the analysis because of its sparse rain gauge network and because most of it is located in the semi-arid and arid zones (all the other zones of interest are characterized by a Mediterranean climate). *** In the central strips only, after cropping the rainfall maps and computing the annual spatial mean for each of the three zones (see figures 6(d)–(f)) we subdivided each of them into two parts: the northern part which contains the Greater Tel Aviv urban area and its downwind region, and the southern part which is characterized by a more open and rural area (see their geographic extent in figure 2(a)). Then, we computed the annual spatial mean for each of the new sub zones (see figure 7).

altitude of 400 m,[3] and was divided into two parts: northern upwind slopes (Nu) that also included the stations at the mountain top, and northern downwind slopes (Nd) that are located more than 1 km east of the watershed line[4]. In this study, precipitation on both Nu and Nd were compared with the northern coastal region (Ns); a narrow strip of land along the coast (<5 km from seashore) located upwind of the Upper Galilee Mountains.

The criterion used for the mountains in central Israel was the same as the one in the north; however, only the upwind slopes and mountain top stations were used (Cu), because of the insufficient number of rain gauge stations on the downwind slopes and the arid nature of this region. The central coastal region (Cs, central shore) was defined as a narrow strip, similar to the one in the north. Parallel to it, we defined another strip located about 10–15 km inland (Cp, central plain), mostly downwind of the Greater Tel Aviv urban region. The separation into Cs and Cp was required in order to better identify any potential urban effects in the central plain.

The central coastal plain is not urbanized homogeneously. The northern portions of the central mountains (the Samaria Mountains) are located downwind of the main urban areas of Israel while the southern portions (the Judean Mountains) are located downwind of a less urbanized region, although polluted to some extent. For this reason the central region was subdivided into two parts. The analysis was carried out once for the region as a whole and then repeated for each part separately (see all the study regions in figure 2(a)).

In addition to evaluating the ratio of the average annual precipitation between the different regions, we also mapped

[3] In *all* analyses referring to the height criterion we placed smooth height values instead of using single point height because the orographic enhancement of precipitation responds predominantly to increase in general elevation. Smoothing was performed for an average height with an area of 16 km^2 around each cell following the procedure of Halfon and Kutiel (2004), who found that this type of averaging gives the highest correlation between altitude and amounts of annual precipitation at stations in northern Israel.

[4] Data from the Golan Heights are only available since 1968, therefore, this region has not been included in the present analysis.

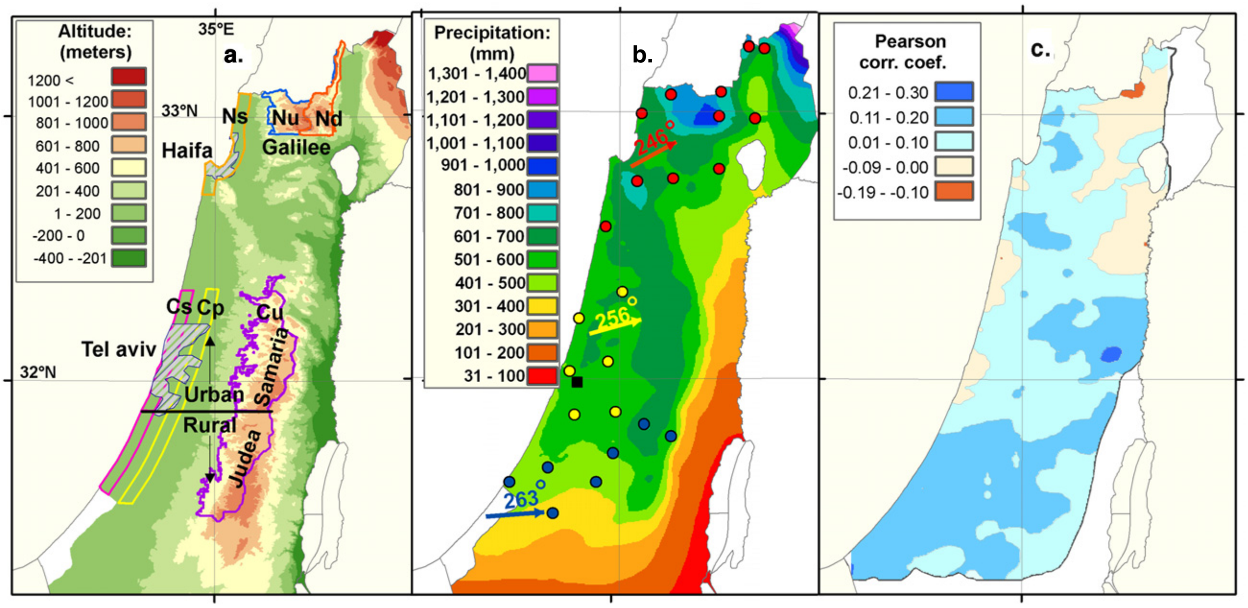

Figure 2. The study area. (a) Physical map and zones of interest for this research. (b) Annual precipitation map and mean wind direction at 850 hPa level during rain[5] . (c) Temporal trend of annual rainfall during the study period.

the temporal trend of precipitation in each cell of the annual rainfall maps. This was done by sorting the 54 annual rainfall grids chronologically (figure 2(c)).

2.2. Method 2—multi-parameter regression

The method of multi-parameter regression also permitted a comprehensive analysis of the data and served as a backup and validation for the mapping analysis (Method 1) described above. In this method the spatial variation of the amounts of annual precipitation in the rainfall stations was described as a function of geographical parameters such as latitude, distance from the seashore (equivalent to longitude) and topographical height (averaged over 16 km^2 around each station).

Using all the stations in the research area over northern Israel (see figure 3(a)) we calculated by regression analysis the main rainfall controlling factors for all 54 years of the study.

The two most important variables that were obtained in the regression analysis were the topographical height (significant in all the years) and the distance from the seashore (significant in 52 out of 54 years). The orographic enhancement of precipitation and the decline of precipitation with distance from the seashore both depend on the precipitation in each specific year. We therefore tested the temporal variations of these two factors in relation to the mean annual amount of precipitation in all the northern seashore stations (0–4 km from the sea) in each year (see figures 3(b)–(e))[6].

In addition to the general evaluation of the variation in orographic precipitation in northern Israel, we also evaluated more specifically the changes in the orographic contribution to rainfall amounts on the upwind slope (western) and downwind slope (eastern) of the Galilee Mountains. For this purpose we sampled all the rain gauge stations on both slopes of the Upper Galilee that are over 350 m above sea level (asl). For each year, the residuals between the measured and calculated amounts based on the regression formula were determined, leaving out the coefficient of the orographic influence. The annual orographic enhancement was calculated by dividing the residuals in each station by the station's height. This annual value was then averaged separately for the stations located on the upslope (including the crest) and downslope of the mountains. The annual values for each of the slopes were divided by the mean annual rainfall in the northern coast for the reason explained in the paragraph above (figures 3(d) and (e)).

2.3. Method 3—mean regional observed rainfall

Method 2 could not be used in the central part of Israel because the mountain, the coast and the seashore regions have different distributions of rain gauge stations. Most of the stations are located in the coastal and seashore regions and there are only a very few stations on the east side of the watershed line. This makes it difficult to develop a reliable regression formula to explain the spatial variation of rain by geographical factors (topography, latitude, and distance from the seashore) as done in the north of the country (less than 50% of the annual explained variance in comparison to 65–75% in the north). We

[5] Mean wind direction for central and southern coastal plain was computed by the sounding data of Bet Dagan (marked by a black square) during rainy days within the period 1957–2004 (using two measurements per day: 11z and 23z). The mean data were weighted separately by the mean daily yields in the southern stations (marked by blue) and in the central stations (marked by yellow). The wind direction during rain in northern Israel was computed after averaging the sounding measurements in Bet Dagan and Beirut airport (location 33, 50′N 35′29E) during days with parallel measurements in both sites within the period 1957–2004. The sounding data were weighted by the mean daily rainfall yields in 11 northern stations (marked by red).

[6] The shoreline is a good indicator for annual potential of precipitation because almost all the rainfall in the study area comes from maritime clouds traversing the coastline on their way inland (Goldreich *et al* 2004).

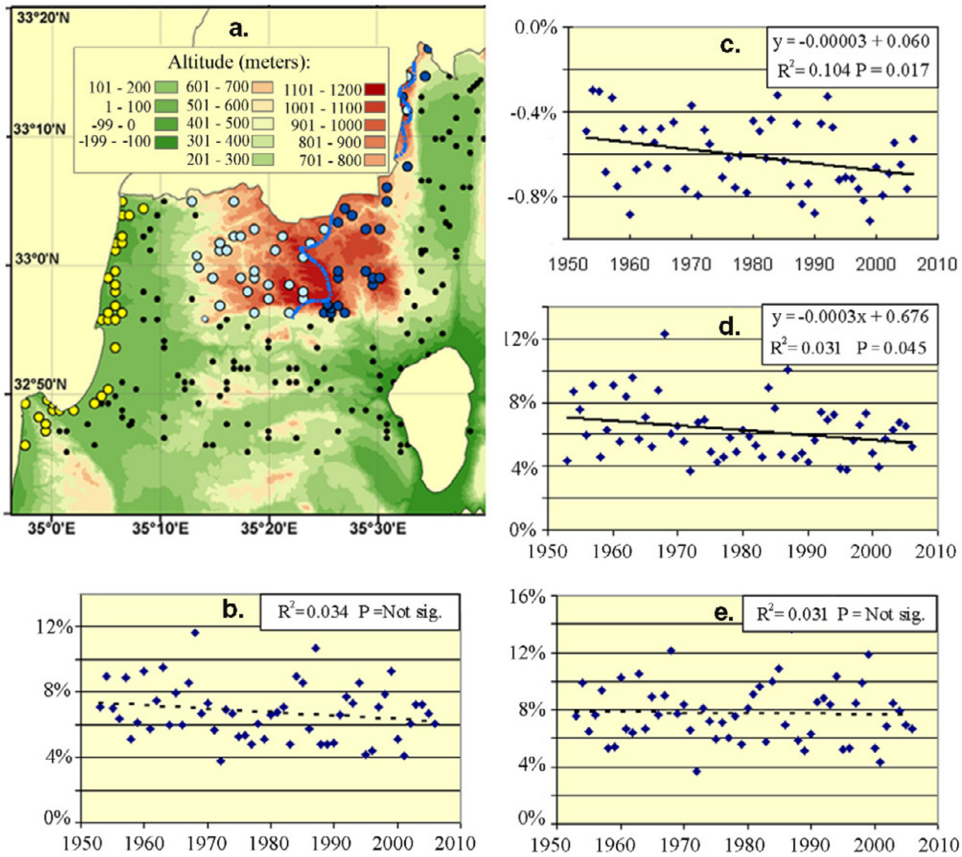

Figure 3. (a) Location of rain gauges used in multi-regression equations fitted in order to describe the annual rainfall distribution by three geographical factors: altitude, distance from shore and latitude. (b) Annual orographic enhancement for 100 m of altitude in comparison to the annual precipitation of the northern coastal stations (marked in yellow). (c) Annual precipitation decline with distance from the shoreline (compared to the mean annual precipitation in the coastal stations). (d) As in (b) but only for Galilean downwind stations (marked in dark blue). (e) As in (b) but only for Galilean upwind stations (marked in pale blue). See method in section 2.

therefore used a different method for this region. For each year all measurements in the central coastal strip (0–4 km from shore), the inner coastal plain (8–16 km from shore) and the Samaria Hills (>350 asl) were averaged separately. Annual ratios between these three regional averages were computed and temporal trends of these ratios were recorded (see figure 4)[7].

Since some of the stations have been relocated from one place to another during the study period, and it was impossible to neutralize this effect with regression calculations, pre-evaluation of the stations was performed. This was done by calculating the annual geographical center of gravity of the stations (the mean altitude, longitude, and latitude of all active stations in a certain year) in each of the three clusters. From figure 4(a) it is clear that the shift in the location of the center of gravity in the three clusters is minor, especially on the east–west axis, which is the most important factor in determining the precipitation in the central coastal plain of Israel. This implies that the small changes are not obstacles for using the method to evaluate the ratio of the mean spatial annual precipitation.

Evaluation of the mean elevation of the mountainous cluster stations during the study period revealed that there was a shift downward (during the years more stations appeared or moved to lower elevation; see figure 4(b)). Since there was no change in the observed mean annual precipitation in the mountainous region it implies that a slightly greater orographic enhancement factor occurred. This is because the same mean precipitation is obtained with stations located lower down.

The stations in Samaria with long records stopped reporting rainfall data in 1998, after 46 years of continuous measurements from 1952.[8] The analysis for this region was therefore, limited to this period. The ratio between the seashore and the inner plane strips was calculated up to 2006.

2.4. Method 4—temporal rainfall ratio trends between individual stations with a long record

This last method consisted of an individual inspection of the temporal trends of the precipitation ratios between each long-lived station in each of the three geographical strips and each station in the other strips. The aim of using this method was

[7] Because of the scattered distribution of the annual ratios, trend lines in this figure and in figures 6 and 7 are calculated based on the least absolute deviations method which is more robust and less sensitive to extreme values compared to the least squares method.

[8] There are a number of new stations in the Israeli settlements in Samaria which are still operating, but their spatial distribution is totally different than the distribution prior to 1998.

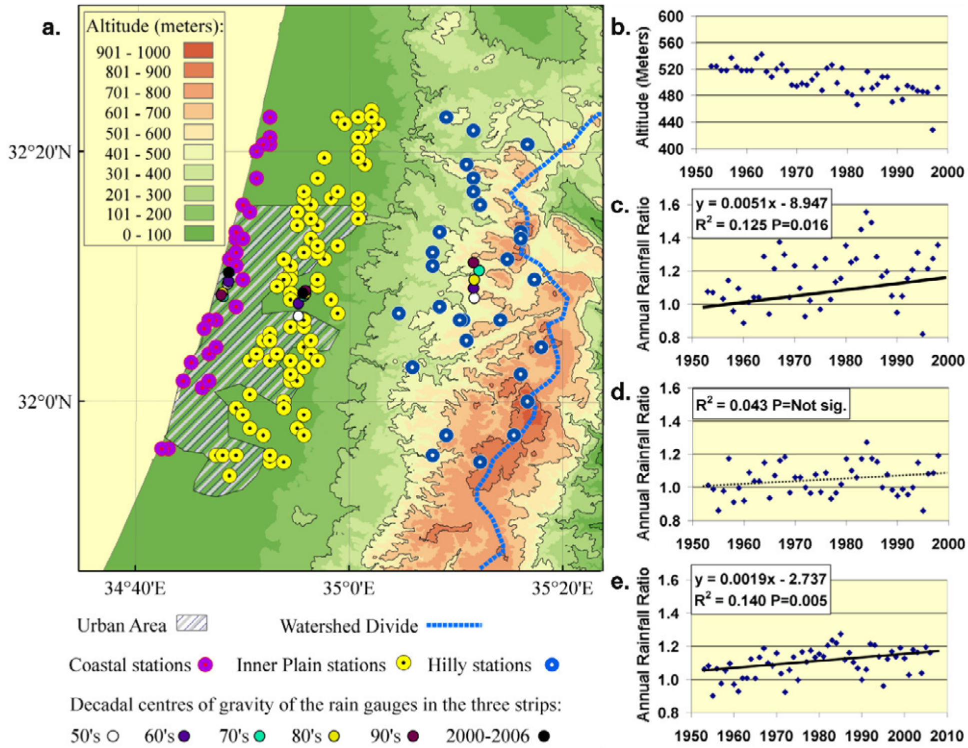

Figure 4. Time series of the ratio between mean annual rainfalls in three strips located next to the most populated area of Israel. (a) Locations of rain gauges. (b) Altitude changes along the study period of the center of gravity of the hilly stations[10] . (c)–(e) Annual ratios between the mean precipitation amounts in hilly and coastal bands stations, hilly and inland bands, and inland and coastal bands, respectively. The temporal trend lines in this figure and in figures 6 and 7 (which also deal with annual ratios) are calculated based on the least absolute deviations method. This method is appropriate for use with such a scattered distribution of the annual ratios because it is more robust and less sensitive to extreme values than the least squares method.

to increase confidence in the results obtained by the other three methods. In order to evaluate temporal trends, only stations with data from over[9] 30–45 years were used, provided that this minimal threshold was obtained almost consecutively (not more than a 2 year break). The rainfall ratio between two stations was calculated only when their simultaneous measurements fitted the above criterion.

After evaluating the precipitation ratios between the different stations (separately for the north and the center of the country), the average slopes and the standard deviation for each region were calculated. Following these calculations, the results were stratified for each station, based on the percentage of cases in which the slopes exceeded one half of the standard deviation above (below) the mean (positive (negative) slopes) and the percentage of slopes that fell within one half of the standard deviation above and below the mean (neutral slopes). The percentage of the ratios in each slope category is presented in figure 5.

[9] In order to obtain a similar number of stations in the three strips in northern and central Israel, we chose a flexible criterion for selecting stations. In the plains, where more rain gauges were available, a station was selected if data were available from a period of at least 45 years. In the mountainous region the minimum number of years was set at 30 in the northern mountains and 40 in the central ones.

[10] Most of the Samaria Hills stations stopped reporting rainfall in 1998. For this reason except for (e) (which does not involve the data from Samaria) all the other time series in figure 4 end in 1998.

3. Results

Before discussing in detail the results for each region, one general observation emerges from figure 2(c): almost all of the research area is characterized with minor temporal correlation coefficients (−0.1–0.2), implying that *no* significant temporal change of the annual rainfall had occurred at any place in the study area.

In the light of these results we should now focus on the different regions using the methods discussed above.

3.1. Northern Israel

In northern Israel the temporal trend of the rainfall is generally positive over the coastal plain and the western Galilean slopes. The positive values decline eastward, turning to negative over the lee side of the Galilee Mountains (see the temporal trend map in figure 2(c)). Another important fact exposed in figure 2(c) is that the highest positive temporal change was registered a few kilometers downwind of the Haifa Bay urbanized zone and not onshore.

Evaluation of the annual rainfall ratio between the different topographical regions in northern Israel is illustrated in figure 6, which shows that during the years there was no significant change in the ratios between the upslope of the Galilee Mountains (western Galilee) and the coastline strip (figure 6(a)). Similarly, no significant trend was observed in

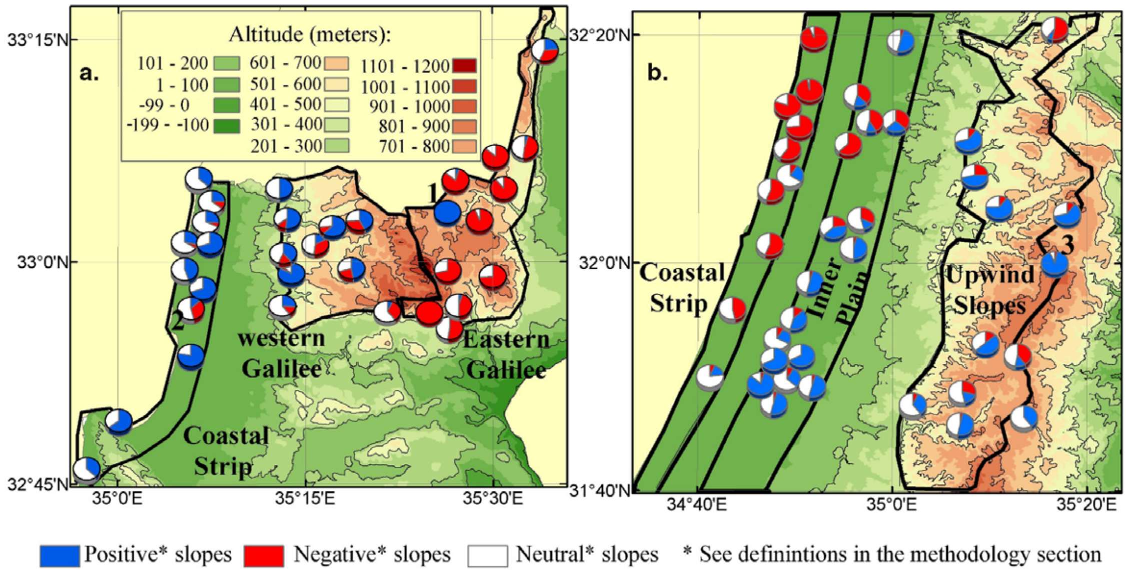

Figure 5. Temporal trend frequencies of the ratio between annual rainfall in long record stations and each of the stations in the parallel bands in northern Israel (a) and central Israel (b). For instance, for each map, a station marked with a full red circle indicates that ALL the slopes of this station's rainfall ratio with ALL the indicated stations are negative. Outstanding stations relative to the trends in their neighborhood (numbered 1, 2 and 3) are referred to in the text and are named Baram (6a), Shomrat (6a) and Mazrat e-Sharqia (6b), respectively. Such cases could result from measurement problems or from occasional mesoscale storms that coincidentally precipitated more over this station than over its surrounding areas. It worth noting that randomly sampling these stations in order to represent the regional rainfall regime can cause misleading interpretations of the climatic situation in the respective area.

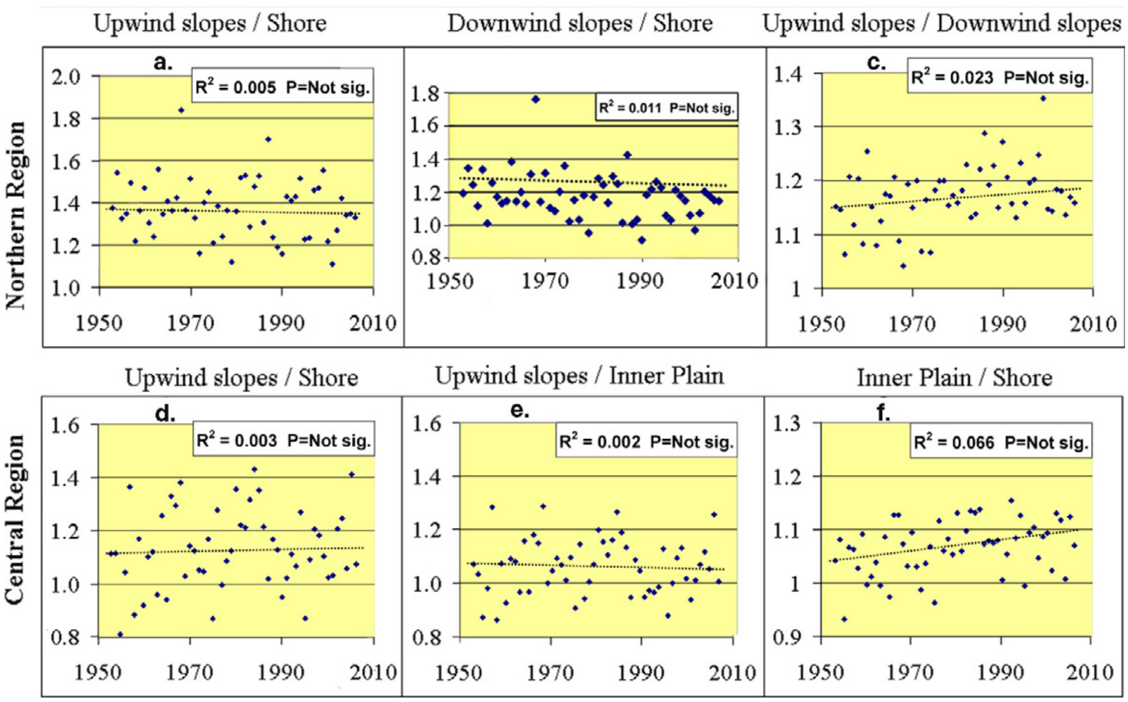

Figure 6. Time series of the ratio between the mean annual rainfall of geographical bands in Israel: (a) northern upwind slopes (Nu)/northern shore (Ns); (b) northern downwind slopes (Nd)/northern shore; (c) northern upwind slopes/northern downwind slopes; (d) central upwind slopes (Cu)/central shore (Cs); (e) central upwind slopes/central plain (Cp); (f) central plain/central shore (see exact location in figure 2(a)). In (a) and (b), the year 1968 stands out with a very high value illustrating the high spatial variability of precipitation even in regions located very close to each other and on the same track of the precipitating clouds.

the ratio between the annual precipitation on the lee side of the Galilee Mountains (eastern Galilee) and the northern coastal strip (figure 6(b)). A slight and insignificant increasing trend in the annual precipitation ratio is observed in Galilee itself, between the western slopes of the Galilee Mountains and the lee slopes (figure 6(c)).

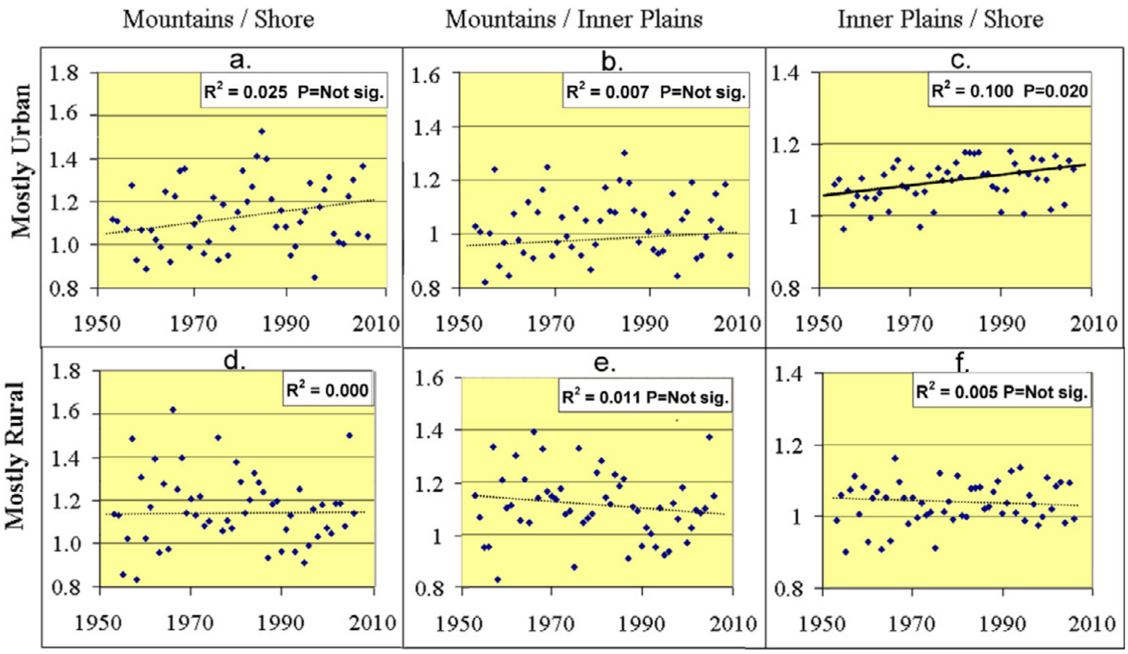

Figure 7. Precipitation ratios in central Israel when separating the region into two sub-regions, northern (urban) and southern (mostly rural).

The results obtained by the multi-regression analysis method for the north of Israel (figure 3) generally agree with the results obtained using the different mapping methods. A tiny and totally insignificant decrease in the orographic enhancement is shown in figure 3(b). The mean orographic enhancement in rain during the research period was 35–40 mm (6–7% from the annual amounts onshore) for every 100 m elevation.

A statistically significant ($P < 0.05$) decrease in rainfall is found with distance from the seashore (see figure 3(c)). A more in-depth view of the changes in rainfall over the upwind slope (western) against the downwind slope (eastern) of the Galilee Mountains during the years of this analysis shows that the annual orographic enhancement over the western slopes remained relatively high and stable (48 mm or 8% from the coastal annual amounts for every rise of 100 m in elevation). In the eastern slopes a slight *decrease* of the orographic enhancement was observed. This decrease was steeper than the average decrease for the whole of northern Israel, but its significance was still very marginal ($P = 0.045$) (figures 3(d) and (e)).

The results obtained from the spatial averaging methods were supported by the examination of individual slopes applied only to stations with long and reliable records (see section 2). In figure 5(a), which depicts the results for the north of Israel, the high percentage of negative slopes as a function of time between the lee side stations and stations to the west (upwind slope and coastal strip) are obvious. Between the coastal and western slope strips, however, there is no distinct difference in the slopes; in both regions they tend to be positive.

3.2. Central Israel

The results obtained from the GIS analysis (Method 1) suggest that in central Israel, as in southern Israel, there is a slight and insignificant increase in the rainfall without any correlation between altitude and the temporal change in rainfall. This slight positive temporal trend of the annual rainfall extends from the inner coastal plain eastward (see figure 2(c)) without dramatic changes between the values obtained at the bottom of the mountains and the values on the mountains top. Along the coastal plain there is a relatively sharp gradient between negative temporal correlation values obtained near the coastline and the positive values in the inner coastal plain. When examining spatial means of the annual rainfall maps, no significant change in the annual precipitation ratio between the upwind slope and the seashore regions was found. On the other hand, a slight increase was observed in the ratio between the inner coastal plain and the seashore (see figure 6(f)). Subdividing the central part into northern and southern regions and analyzing each one separately (see figure 2(a)) revealed that to the northern and urbanized zone there is an increasing trend but it is not significant between the *upwind slopes* and the *seashore*, whereas in the southern part, downwind to the more open shore (Judean Mountains), the linear trend of the orographic ratio is almost horizontal throughout the study period (see figure 7).

When examining the ratio between the *inner plains* and the *seashore* in these two parts of the central region a significant increase ($P = 0.020$) was found in the northern urban part whereas in the southern and mostly rural part no temporal trend could be distinguished (see figure 7).

The results of the mapping method concerning the northern and the most urbanized zone in the central area of Israel were supported by the mean regional measured rainfall (see section 2). Examination of the spatial mean precipitation in the different strips downwind of the urban region of Tel Aviv (figure 4) shows that the precipitation ratio between the mountainous strip and the inner plain as well as the seashore did not decrease at all. In fact, just the opposite, where the ratio between the Samaria upwind slope and the seashore strip shows a significant increase ($P = 0.016$ see figure 4(c)). It is worth noting that figures 4(c) and 7(a) show that the orographic ratios have short term nonlinear fluctuations during the study period that are not correlated with anthropogenic effects such as the continuous increase in the population of the Greater Tel Aviv region during the study period.

A more linear and statistically significant increase was found in the ratio between the annual precipitation in the inner coastal strip against the seashore stations (figure 4(e)). This corroborates the results obtained with the mapping method (Method 1), but with even higher statistical significance ($p = 0.005$).

The negative temporal changes of the rainfall on the shoreline in comparison with the plains and mountains downwind of the Greater Tel Aviv urban area is also evident from the slopes method (figure 5(b)). Most of the slopes of the rainfall ratios between coastal stations and inland strips (inner plain and Samaria) were negative. Positive slopes in the coastal strip were obtained just in the southern edge of the central region south of the Greater Tel Aviv area (figure 5(b)). This explains the positive tendency of the temporal rainfall ratios between stations in both mountainous and inner plain strips and stations in their adjacent strips (figure 5(b)).

4. Discussion

The main findings of this study are in agreement with previous works over the past few decades. The weak positive (increase) trends in rainfall that we observed in the southern area are in agreement with similar findings in the south-western part of the research area by Ben-Gai *et al* (1994, 1998), Steinberger and Gazit-Yaari (1996), Zangvil *et al* (2003) and Alpert *et al* (2008), although these investigations were conducted over periods that are somewhat different from the present one. On the other hand, the reported decrease in precipitation in northern Israel (Ben-Gai *et al* 1994, 1998, Steinberger and Gazit-Yaari 1996, Givati and Rosenfeld 2005) was found only in the eastern part of the Galilee Mountains, and not on the western slopes or in the northern coastal strip. The difference between the above studies and the present one could be related to the different periods analyzed or to the fact that in these studies the Galilee region was analyzed as if it is one homogeneous region, thus smoothing local variations that were found in the present work. Furthermore, since the eastern Galilee has a high concentration of rain gauges, previous studies have given it a higher weight than other northern regions.

The present results confirm, with higher resolution, the results of Alpert *et al* (2008) and strengthen their conclusion that contradicts the works of Givati and Rosenfeld (2004, 2005), suggesting that suppression of precipitation occurred and that it is attributed to the effects of air pollution on orographic precipitation.

The decrease in rainfall over the lee slopes of the Galilee Mountains that was reported by Givati and Rosenfeld (2005, 2009) was also observed here but is not significant. According to Givati and Rosenfeld (2004) lee slopes should have received some increases in precipitation as a compensation for the suppression that should occur on the upwind slopes. However, in this study no decrease in rainfall ratio between the upwind slopes of the mountains against the coastal regions was found. It is shown here that downwind of the main urban region of Israel (Tel Aviv) an increase in the ratio of mountain precipitation to the coastal region occurred (significant by one method and insignificant by others),

One of the main reasons that Givati and Rosenfeld (2004) found the opposite trends in the central part of Israel is related to the choice of stations to represent the upwind region of the mountain. They chose stations located in and slightly downwind of the urban region, stations that have been shown here and by Alpert *et al* (2008) to have an increased precipitation ratio against the seashore stations. Southward to the Greater Tel Aviv urbanized area the rainfall ratio between the inner plains and the coast remained unchanged, supporting the urban rainfall enhancement. These findings are in agreement with earlier reports by Goldreich (1981, 1995, 2004) and Goldreich and Manes (1979) who also suggested that urban effects could be responsible for an increasing trend in precipitation downwind of the Tel Aviv urban sprawl.

Downwind of Haifa Bay we also observe a narrow strip with a relatively higher temporal rainfall change with respect to its surrounding area. This is also in line with Goldreich (1990) who argued that this specific area had undergone the strongest positive change between the rainfall averages of 1931–1960 and those of 1961–1990, suggesting that it was the result of urban enhancement. It should be stated, however, that according to the present findings, the rainfall enhancement downwind of the Haifa urban area is insignificant.

Most reports about urban effects on precipitation around the world were related to summer convective precipitation. The fact that similar effects are shown to be operating in winter storms in the eastern Mediterranean is in agreement with the work of Altaratz *et al* (2001) who showed that in this region convective activity and the development of thunderclouds reach their maximum intensity in the winter season.

In addition to the urban explanation of the rainfall trend between inner plains and the coast (increasing instability, changes in friction and mechanical convection, etc) there could also be other dynamical explanations such as variations in the interaction of synoptic flows with coastal convergence. The south-eastern coast of the Mediterranean creates a region of convergence that enhances convection (Rosenfeld 1986, Sharon and Kutiel 1986, Alpert and Getenio 1988, Khain *et al* 1993, 1996). Although the increase in precipitation appears near the coast (Rosenfeld 1986), there is a short time lag until the rainfall enhancement caused by the convergence is seen at the ground. Thus, the maximum rainfall appears a few kilometers downwind of the coast (Goldreich 1994). Strengthening of the convergence zone in the eastern Mediterranean due to thermal or dynamical changes (that have nothing to do with local anthropogenic effects) can increase the difference in precipitation between the inner coast and the sea. On the other hand, the fact that this increasing ratio trend reaches its peak downwind of the major urbanized areas and is

Table 1. Comparison of the present results to the orographic rainfall suppression theory.

Region in Israel	Method	Result	Expected result by the urban suppression theory
North	Temporal correlation trends (figure 2(c))	*Small positive* values on the upwind slopes *Small negative values* on all parts of the downwind slopes	*Negative* values on the upwind slopes *Positive values* on parts of the downwind slopes
	Mapping annual ratio between regions (figures 6(a)–(c))	Ratio upwind slopes/coast: *stable* Ratio downwind slopes/coast: *almost stable* Ratio upwind slopes/downwind slopes *insignificant increase*	Ratio upwind slopes/coast—*significant decrease* Ratio downwind slopes/coast ∼ stable Ratio downwind slopes/upwind slopes *significant decrease*
	Regression (figure 3)	*No reduction* of the orographic enhancement on the upwind slopes Decrease (marginally significant) on the downwind slopes	*Significant reduction* of the orographic enhancement on the upwind slopes Little changes on the downwind slopes
	Slopes (figure 5(a))	*Positive* in the shore stations *Mostly positive* on the upwind slopes *Negative* on the downwind slopes	*Positive* in the shore stations *Negative* on the upwind slopes *Mixed* on the downwind slopes
Center	Temporal correlation trends (figure 2(c))	*Small negative values* in the shore upwind of the urban area and *positive values* downwind of the urban area (inner plains and upwind slopes)	*Positive values* in the coastal plain (shore and inner plains) and *neutral or negative* values in hilly stations downwind of the urban area
	Mapping annual ratio between regions (figures 6(d) and 7)	Ratio: upwind slopes/coast—*insignificant increase*	Ratio: upwind slopes/coast—*significant decrease*
	Measurements spatial average (figure 4)	Ratio: upwind slopes/coast—*significant increase*	Ratio: upwind slopes/coast—*significant decrease*
	Slopes (figure 5(b))	Mostly negative in the shore stations Mostly positive in the mountainous upwind stations	Positive in the shore stations Negative in the mountainous upwind stations

continuous from prior periods as reported by (Goldreich 1981, 1995), suggests urban effects on precipitation.

Regardless of the reasons for the differences between the seashore and the inner coastal strip, evaluation of the orographic enhancement ratio should be carried out between upslope mountainous stations and windward relatively uninterrupted coastal stations. The assumption that the increase in precipitation downwind of the city should be accompanied by a similar or greater increase in precipitation on the upwind slopes of the mountain (Givati and Rosenfeld 2004, 2005) is problematic, especially in Israel.

The competing effects on the potential rainfall between the coastal convergence enhancement and the orographic enhancement further inland cause seasonal changes in the rainfall distribution in Israel (Goldreich 2004). The convergence near the shore plays a major role in determining the rainfall at the beginning of the rainy season when sea–land temperature differences are the highest. Later on, into the rainy season, the coastal convergence decreases and the potential contribution to the orographic precipitation gradually increases (Kutiel 1987, Khain *et al* 1993).

Assuming that this seasonal principle of rainfall competition applies to long-range variations in precipitation, the fact that the orographic enhancement remains unchanged in spite of the increase in the convergence near the coast emphasizes that the hypothesis that orographic rainfall suppression occurs in Israel is not substantiated.

As shown above, there are two schools of thought about the anthropogenic effects on precipitation in Israel. One school argues that urban regions enhance downwind precipitation and the other proposes that the urban air pollution is responsible for decreases in orographic rainfall. The present results support the idea that it is the urban effects that enhance precipitation. Tables 1 and 2 summarize the results obtained by the different methods and compare them to the expected results based on the theories of precipitation suppression downwind of pollution sources (e.g. Givati and Rosenfeld 2004, 2005, 2007) and urban enhancement of precipitation (e.g. Goldreich 1995,

Table 2. Comparison of the present results to the urban enhancement theory.

Region in Israel	Method	Result	Expected result by the urban enhancement theory
North	Temporal correlation trends (figure 2(c))	Maximal *positive* values in the inner plain downwind of Haifa urban area	Maximal *positive* values downwind of Haifa urban area
Center	Temporal correlation trends (figure 2(c))	Positive values in the inner plains downwind of Greater Tel Aviv urban area Also, an apparent maximum in the east of Samaria (but with insufficient observations, see section 2)	Maximal positive values in the inner plain downwind of Greater Tel Aviv urban area
	Mapping annual ratio between regions (figure 7)	Ratio: inner plain/coast-downwind of the urban area: *significant increase* Ratio inner plain/coast-downwind of rural areas: *stable*	Ratio inner plain/coast downwind of the urban area: *significant increase* Ratio inner plain/coast—downwind of rural areas: *stable*
	Measurements spatial average (figure 4(e))	Ratio inner plain/urban coast—*significant increase*	Ratio inner plain/urban coast—*significant increase*
	Slopes (figure 5(b))	*Negative* in the urban shore stations *Mostly positive* downwind of the urban area	*Mostly negative* in the shore stations *Positive* downwind of the urban area

2003, Goldreich and Manes 1979, Goldreich and Kaner 1991), respectively.

5. Implications for artificial rain enhancement in Israel

The gradual change of the temporal trend values from positive ones in the western slopes of the Galilee Mountains into negative ones in their eastern slopes (see figure 2(c)) may have occurred due to fluctuations in synoptic conditions such as recent pressure increases and weakening of cyclonic trends in the eastern Mediterranean (Mandel *et al* 2006, Alpert *et al* 2004, Trigo *et al* 2000, Zangvil *et al* 2003), urban positive effects upwind of the lee slopes and more. However the fact that no other mountainous region besides the eastern Galilee experienced a temporal decrease in the precipitation raises questions about the effectiveness of the operational cloud seeding in Israel which aims to enhance the rainfall, particularly in this region (Gagin and Neumann 1981).

These results fall in line with other reports critical of the rain enhancement operation in Israel (Rangno and Hobbs 1995, Levin *et al* 1996, Kessler *et al* 2006, Sharon *et al* 2008). Nonetheless it is clear that in order to better evaluate the influence of cloud seeding on precipitation in northern Israel a study stratifying the daily rainfall data based on different seasons and synoptic conditions should be conducted.

6. Conclusions

This research investigated temporal variations of precipitation in Israel over the last 60 years using four different methods that take advantage of *all* the available data.

The main results obtained from the different methods were almost identical, namely that temporal rainfall enhancement occurred immediately downwind of the urban regions. On the other hand it does not support the hypothesis that urban pollution in Israel suppresses orographic precipitation.

The analysis shows that the only place where a slightly decreasing trend in annual rainfall amounts was detected is in the lee (eastern) side of the Galilee Mountains. This finding is important because this area has been the target of the cloud seeding experiments and operations for the past 50 years. The fact that rainfall actually decreased in this area in comparison to the surrounding unseeded regions raises questions about the effectiveness of the seeding operations in the north of Israel, suggesting that unless synoptic conditions were significantly changed in recent decades, cloud seeding had no positive effect on the amounts of precipitation in the designated target area.

References

Alpert P and Getenio B 1988 One-level modeling for diagnosing surface winds over complex terrain. Part I: comparison with 3D modeling in Israel *Mon. Weather Rev.* **116** 2025–46

Alpert P, Halfon N and Levin Z 2008 Does air pollution really suppress precipitation in Israel? *J. Appl. Meteorol.* **47** 933–43

Alpert P, Osetinsky I, Ziv B and Shafir H 2004 Semi-objective classification for daily synoptic systems: application to the eastern Mediterranean climate change *Int. J. Climatol.* **24** 1001–11

Altaratz O, Levin Z and Yair Y 2001 Winter thunderstorms in Israel: a study with lightning location systems and weather radar *Mon. Weather Rev.* **129** 1259–66

Ben-Gai T, Bitan A, Manes A and Alpert P 1994 Long-term changes in annual rainfall patterns in southern Israel *Theor. Appl. Climatol.* **49** 59–67

Ben-Gai T, Bitan A, Manes A, Alpert P and Rubin S 1998 Spatial and temporal changes in rainfall frequency distribution patterns in Israel *Theor. Appl. Climatol.* **61** 177–90

Changnon S A, Huff F A, Schickedanz P T and Vogel J L 1977 Summary of METROMEX, vol I: weather anomalies and impacts *Illinois State Water Survey Bull.* **62** 264 pp

Changnon S A, Semonin R G, Auer A H, Braham R R and Hales J M 1981 *METROMEX: A Review and Summary* (*Meteorological Monograph* vol 40) (Boston: American Meteorological Society) p 181

Changnon S A, Semonin R G and Huff F A 1976 A hypothesis for urban rainfall anomalies *J. Appl. Meteorol.* **15** 544–60

ESRI Inc. 2004 *ArcMap™9.0* Environmental Systems Research Institute Inc., Redlands, CA

Gagin A and Neumann J 1981 The second Israeli randomized cloud seeding experiment: evaluation of the results *J. Appl. Meteorol.* **20** 1301–11

Givati A and Rosenfeld D 2004 Quantifying precipitation suppression due to air pollution *J. Appl. Meteorol.* **43** 1038–56

Givati A and Rosenfeld D 2005 Separation between cloud seeding and air pollution effects *J. Appl. Meteorol.* **44** 1298–314

Givati A and Rosenfeld D 2007 Possible impacts of anthropogenic aerosols on water resources of the Jordan River and the Sea of Galilee *Water Resources Res.* **43** W10419

Givati A and Rosenfeld D 2009 A comment on ‘Does air pollution really suppress precipitation in Israel?’ *J. Appl. Meteorol.* **48** at press

Goldreich Y 1981 The urban effect as an additional factor determining rainfall spatial distribution in Israel *Isr. Meteorol. Res. Pap.* **3** 193–202

Goldreich Y 1990 The 1961–1990 rainfall normals, their annual march and relevance to the urban climate in Israel *Isr. J. Earth Sci.* **39** 85–92

Goldreich Y 1994 The spatial distribution of annual rainfall in Israel—a review *Theor. Appl. Climatol.* **50** 45–59

Goldreich Y 1995 Urban climate studies in Israel—a review *Atmos. Environ.* **29** 467–78

Goldreich Y 2003 *The Climate of Israel. Observation, Research and Applications* (New York: Kluwer Academic/Plenum) p 298

Goldreich Y 2004 Spatial distribution of mid-season rainfall date in Israel—a review *Horiz. Geogr.* **60/61** 177–82

Goldreich Y and Kaner M 1991 Advertent/inadvertent effect on ‘Rainfall Center’ displacement in the Northern Israel *Atmos. Environ.* B **25** 301–9

Goldreich Y and Manes A 1979 Urban effect on precipitation patterns in the Greater Tel-Aviv area *Arch. Meteorol. Geophys. Bioclimatol.* B **27** 213–24

Goldreich Y, Moses H and Rosenfeld D 2004 Radar analysis of cloud systems and their rainfall yield in Israel *Isr. J. Earth Sci.* **53** 63–76

Halfon N and Kutiel H 2004 Precipitation mapping in a mountainous topography: the case of northern Israel *Horiz. Geogr.* **62** 33–49 (in Hebrew—English abstract)

Hindman E E, Hobbs P V and Radke L F 1977 Cloud condensation from a paper mill. Part II: calculated effects on rainfall *J. Appl. Meteorol.* **16** 753–5

Hjemfelt M R 1982 Numerical simulation of the effects of St Louis on mesoscale boundary-layer airflow and vertical air motion: simulations of urban versus non-urban effects *J. Appl. Meteorol.* **21** 1239–57

Hobbs P V, Radke L F and Shumway S E 1970 Cloud condensation nuclei from industrial sources and their apparent influence on precipitation in Washington State *J. Atmos. Sci.* **27** 81–9

Huff F A 1977 Urban effects on storm rainfall in Midwestern United States *Proc. Amsterdam Symp., IAHS-AISH 123* pp 12–9

Kessler A, Cohen A and Sharon D 2006 Assessment of the effect of operational cloud seeding in northern Israel *Abstract (in English) of the Full Report Entitled: Analysis of the Cloud Seeding Effectiveness in Northern Israel, Report to the Israeli Water Authority, Environmental & Water Resources Eng. (2006) (Haifa)* p 117 (in Hebrew)

Khain A P, Rosenfeld D and Sednev I 1993 Coastal effects in the eastern Mediterranean as seen from experiments using a cloud ensemble model with detailed description and ice microphysical processes *Atmos. Res.* **30** 295–319

Khain A P, Sednev I and Khvorostyanov V 1996 Simulation of coastal circulation in the eastern Mediterranean using a spectral microphysics cloud ensemble model *J. Clim.* **9** 3298–316

Krichak S O, Kishcha P and Alpert P 2002 Decadal trends of main Eurasian oscillations and the eastern Mediterranean precipitation *Theor. Appl. Climatol.* **72** 2002–20

Kutiel H 1987 Rainfall variations in the Galilee (Israel). I—variations in the spatial distribution in the periods 1931–1960 and 1951–1980 *J. Hydrol.* **94** 331–44

Levin Z, Ganor E and Gladstein V 1996 The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean *J. Appl. Meteorol.* **35** 1511–23

Mandel M, Alpert P and Osetinsky I 2006 Assessing the eastern Mediterranean mesoscale circulation by clustering the daily weather *The Annual Mtg of Israel Meteorological Society (Tel Aviv, March 2006)* p 5 (Available at: http://ims.huji.ac.il/abstracts2006/MosheMandel1.pdf)

Rangno A L and Hobbs P V 1995 A new look at the Israeli cloud seeding experiments *J. Appl. Meteorol.* **34** 1169–93

Rosenfeld D 1986 The dynamic characteristics of cumuliform clouds and cloud systems and their effect on the rainfall precipitated by them *A Thesis Submitted for the Degree Doctor of Philosophy* Hebrew University in Jerusalem, Jerusalem, p 143

Shafir H and Alpert P 1990 On the urban orographic rainfall anomaly in Jerusalem—a numerical study *Atmos. Environ.* B **24** 365–75

Sharon D, Kessler A and Cohen A 2008 The history and recent revision of Israel’s cloud seeding program *Isr. J. Earth Sci.* **57** 65–9

Sharon D and Kutiel H 1986 The distribution of rainfall intensity in Israel, its regional and seasonal variations and its climatological evaluation *J. Climatol.* **6** 277–91

Shepherd J M and Burian S J 2003 Detection of urban-induced rainfall anomalies in a major coastal city *Earth Interact.* **7** 4

Shepherd J M, Pierce H F and Negri A J 2002 Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite *J. Appl. Meteorol.* **41** 689–701

Steinberger E H and Gazit-Yaari N 1996 Recent changes in the spatial distribution of annual precipitation in Israel *J. Clim.* **9** 3328–36

Thielen J, Wobrock W, Gadian A, Mestayer P G and Creutin J D 2000 The possible influence of urban surfaces on rainfall development: a sensitivity study in 2D in the meso-gamma scale *Atmos. Res.* **54** 15–39

Trigo I F, Davies T D and Bigg G R 2000 Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones *Geophys. Res. Lett.* **27** 2913–6

Warner J 1968 A reduction in rainfall associated with smoke from sugar-cane fires—an inadvertent weather modification *J. Appl. Meteorol.* **7** 247–51

Warner J 1971 Smoke from sugar-cane fires and rainfall *Proc. Int. Conf. on Weather Modification* (Canberra: American Meteorological Society) pp 191–2

Warner J and Twomey S 1967 The production of cloud nuclei by cane fires and the effect on cloud droplet concentration *J. Appl. Meteorol.* **24** 704–6

Zangvil A, Karas S and Sasson A 2003 Connection between eastern Mediterranean seasonal mean 500 hPa height and sea-level pressure patterns and the spatial rainfall distribution over Israel *Int. J. Climatol.* **23** 1567–76