Does Air Pollution Really Suppress Precipitation in Israel?

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ABSTRACT

Trends in the orographic rainfall ratio R_0 over Israel are reevaluated. It is shown that the rainfall has not changed significantly over most of the mountainous stations, with some significant increases over the central mountains. The overall evaluation of R_0 for all potential station pairs, calculating the ratio of each mountain station separately over each coastal or seashore station, indicates that about 50% of all pairs show a positive trend in R_0. The high spatial variability, especially over the mountains, allows for finding orographic rainfall ratio trends that are significant *in both the positive and negative directions*. The correct definition of R_0 in the Israeli case requires the use of a seashore cluster of stations. If some of the seashore stations are replaced by inland stations, and in particular stations that are right over the region of maximum positive rainfall urban enhancement due to the thermal heat island or other urban effects, a seemingly decreasing "orographic ratio" is unavoidable. In such a case, urban dynamical positive effects on coastal rainfall can be erroneously interpreted as pollution suppression of orographic rainfall. When seashore stations are selected as required by a proper definition of the orographic ratio, increasing R_0 is obtained over central Israel and an insignificant trend over the north is found. Furthermore, evaluation of the ratio of rainfall for the upwind in comparison with the downwind side of the Galilee Mountains exhibits an increasing trend, opposite to the recent findings of Givati and Rosenfeld. The rainfall analysis shows no evidence of any suppression of rainfall over the mountains due to pollution, and at least in Israel other factors besides aerosols are predominant in defining the trends in the orographic rainfall ratio.

1. Introduction

The study of the effects of pollution aerosols on precipitation has been in the forefront of scientific research for many years (e.g., Warner 1968, 1971; Gunn and Phillips 1957; Changnon et al. 1971; Changnon 1980). Most measurements show that pollution influences the cloud microphysical processes (e.g., Andreae et al. 2004, and many more) but the final link in the chain leading to precipitation is much more complex, involving interactions of dynamical as well as microphysical processes. Some numerical models that simulate the development of single clouds show that without the presence of giant cloud condensation nuclei (GCCN), pollution tends to reduce precipitation (e.g., Levin et al. 2005; Teller and Levin 2006; Yin et al. 2000, and many more). However, more complex models that treat the dynamical processes more realistically reveal that the interactions of cloud microphysical processes and dynamics sometimes lead to suppression of precipitation while under different meteorological conditions enhanced rainfall is obtained (e.g., van den Heever et al. 2006; van den Heever and Cotton 2007; Tao et al. 2007). Unfortunately, there are only very few reliable measurements that tie the microphysical parameters to changes in precipitation on the ground.

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Recently, Givati and Rosenfeld (2004, hereinafter GR04) reported on results from 50–80 yr of analyzed rainfall data in orographic clouds over California and central Israel. In their report they showed that downwind of polluted regions the ratio of rainfall on the upslope of the mountains to the rainfall downwind of the urban pollution region (named the orographic ratio R_0) exhibited a continuous decrease over the years. The argument posed by GR04 is that this decrease is a result of increased pollution, which reduces the cloud drop size, leading to a delay in the formation of precipitation and thus to a decrease in rainfall on the upslope of the mountains. Furthermore, the delay in precipitation formation, according to GR04, led to a small decrease of rainfall at the mountaintop and an increase on the lee side of the mountain. In a more recent paper Givati and Rosenfeld (2005, hereinafter GR05) analyzed the rainfall amounts in northern Israel. They argued that, similar to their results from central Israel, suppression of orographic rain occurred in the north and that the operational cloud seeding in this region, running continuously since 1975, increased the rain amounts over the target area on the lee side of the Galilee Mountains (the eastern region of the northern box in Fig. 1a) by an equivalent amount to the rain suppression due to pollution.

In this paper, we take a second look at the results of GR04 and GR05 by reanalyzing the rainfall data in Israel by including the same stations used in the original works, adding a few more stations that are in the same locations, thus making the results more robust. Furthermore, in order to validate the results of GR04 and GR05, we also use the same method of analysis (although we think that the method of evaluation is not adequate) and compare it with a more comprehensive evaluation method.

2. Methodology and stations

In this paper, we analyze annual rainfall over the period of 50 yr from 1954 to 2004. Figure 1a presents contours of the precipitation ratio (in %) between two periods: 1979/80–2003/04 and 1954/55–1978/79, using 78 stations. The figure also indicates those stations that were used by us and by GR04 and GR05, for the orographic ratio analyses over central and northern Israel, respectively. In the present study only stations that passed the quality control of the Israel Meteorological Service (IMS) are used for the analysis in Fig. 1a. For the study period, 56 stations had the full 50-yr rainfall dataset; 18 stations had 90%–99% of this dataset. The missing data were completed by precipitation ratio from adjacent stations having high correlations with the pertinent station. Because of a lack of reliable stations in Samaria, four stations (to complete the total aforementioned number of stations, i.e., 78 = 56 + 18 + 4) with partial data from 1952 were also examined without completing their missing data.

The two major urban areas of Israel are located in the central coastal plain around Tel Aviv and near Haifa bay in the north. The study, therefore, focuses on these two regions, as shown in Fig. 1a.

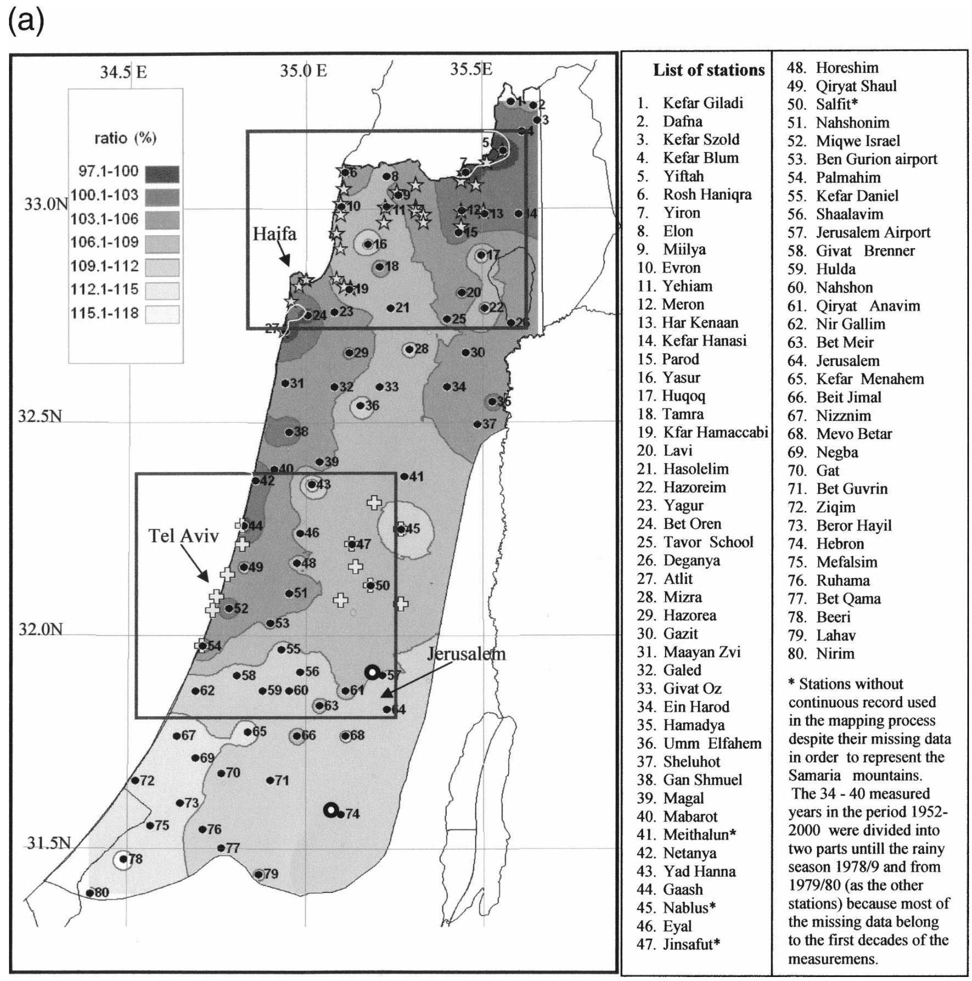
3. Results: General rainfall trends

Comparing the ratio (in percent) of the more recent period (1979/80–2003/04) to the earlier one (1954/55–1978/79), no reduction in mountainous rainfall is noticed in Fig. 1a. In fact, the most noticeable feature is only four small areas with zero change, marked with white lines, encompassing data from only seven gauges. Hence, the rainfall has increased practically everywhere and the largest increases are over the south of the country. In central Israel, there are some rainfall reductions in the seashore strip along with some rainfall increases inland, mainly downwind of the large urban or industrial zones, but still upwind of the mountains.

In particular, we notice 1) that there are no systematic reductions in mountain rainfall; 2) that in the recent period there is some *increase* in the orographic rainfall over central Israel when compared to the seashore strip stations (in which rainfall has decreased); and 3) there is a decrease in the orographic rain ratio when mountain stations are compared to inland stations (here "inland" is used to represent those stations that are located downwind of the seashore, but still upwind of the mountains; see Fig. 1b), because the increase in the inland stations was larger than the increase in the mountain stations. In fact, a most relevant mathematical rule is that this ratio would have decreased even if the rain in both the inland and mountains stations increased by the same amount, as will be shown later. Next, we investigate these apparent decreases in the orographic ratio over central and north Israel.

4. The trends in orographic versus seashore rainfall ratios in Israel

The analyses performed by GR04 and GR05 over the central and north regions of Israel, respectively, will be later shown (sections 5 and 6) to be largely dependent on the selection of the specific stations. To determine if a general trend does exist, we perform a selection-independent test. Figure 2a summarizes the histograms of all temporal trends obtained from all possible pairs of mountain (right), inland (middle) and seashore (left)



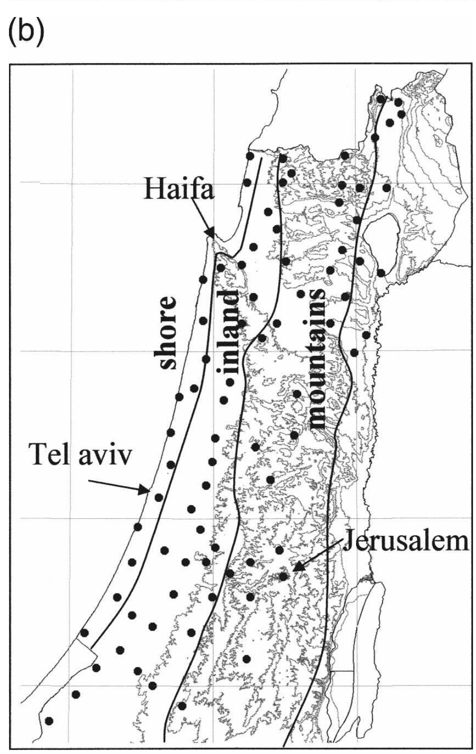


FIG. 1. (a) Contours of the precipitation ratio for the period of 1979/80–2003/04 relative to 1954/55–1978/79. The locations of all 80 stations are indicated on the map but only 78 were used for the actual mapping. The "no change" line (100%) is indicated by white lines showing that the areas with less than 100% ratios are very small and are located near the coast and in the northeastern part of the study area. The three large cities (Jerusalem, Tel Aviv, and Haifa) are noted. The two squares mark the central and northern regions over which this study is conducted. Shown are reliable rain stations that were used in this mapping (⊙, 78 stations); additional stations mentioned in this paper in reference to the GR04 and GR05 findings downwind of the two major urban centers in northern (☆) and central (✣) Israel are also shown. Further details on these stations are given in Figs. 3a and 4a. Two stations (57 and 74, noted by **O**) were analyzed but were not used in the mapping process because they have no data before the mid-1960s. (b) The geographical strips identifying the seashore, inland, and mountains stations of Israel. Altitude contour interval is 200 m.

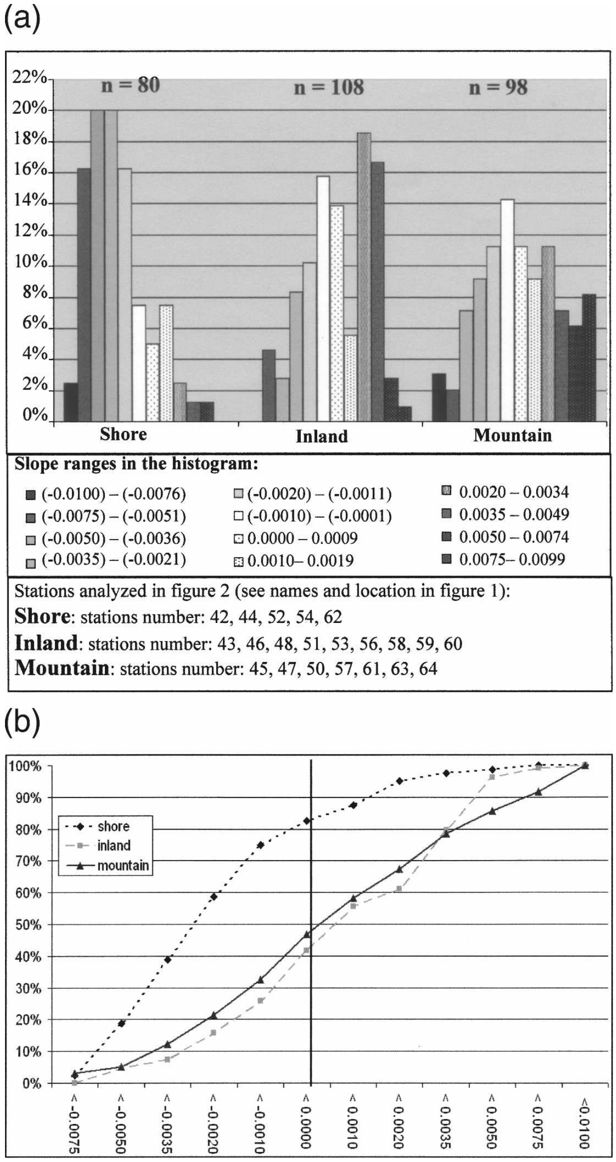


FIG. 2. (a) Histogram for the frequencies of all slope values or time trends of the ratios of all pairs of stations in the three strips (seashore against inland and mountain stations, inland against seashore and mountain stations, and the orographic ratios of mountain against all seashore and inland stations) in the central box of Fig. 1a. For instance, for a seashore station with rainfall R (shore), the trend was calculated as the ratio $R_{sh} = R(\text{shore})/R(\text{pair station})$. Hence, the values of R_{sh} were calculated for each year and then the trend was derived from the slope of the best-fit line. This was repeated for every seashore station against each and every station in the inland and mountain strips. The slope ranges in the histogram and the station numbers in each strip in the central box are listed in the legend. (b) The accumulated frequencies of all trends from the most negative slope upward, for the central box of Fig. 1a and the three strips shown in Fig. 1b.

stations in the three strips (see Fig. 1b) against all stations from other strips, for central Israel. By trends, we mean that we calculate the ratio of each station in the mountain over each inland station and every seashore station. Similarly, we take each inland station and calculate the ratio over each station in the seashore and the mountain. Finally, we take each station on the seashore and calculate the ratio against each inland station and the mountain. Note that only the ratios of mountain stations to those in seashore and in inland stations truly represent orographic ratios.

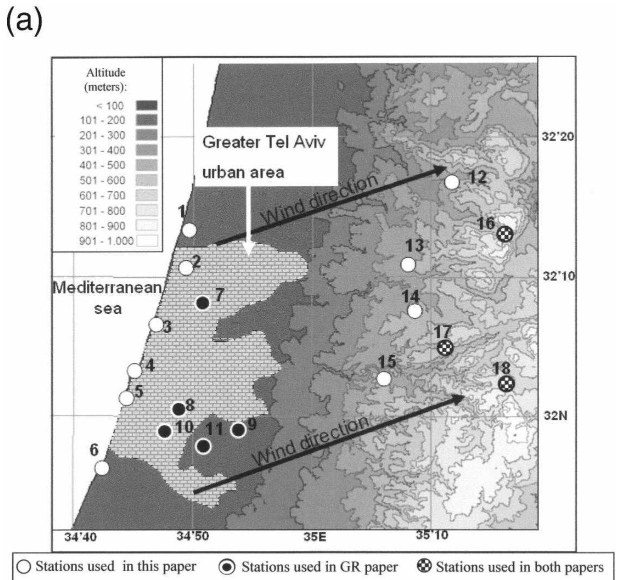
The total numbers of pairs for the three strips indicated in Fig. 1b over central Israel are 98, 108, and 80 (a similar analysis for all of Israel yielded 799, 987, and 470 pairs, respectively, with similar findings; not shown). For instance, the number 98, representing all pairs in the mountain diagram on the right of Fig. 2a, is the result of multiplying the number of mountain stations (7) by the total number of seashore (5) and inland (9) stations, that is, $7 \times 14 = 98$.

Figure 2a shows the results for 21 stations (74 for all of Israel) over central Israel; the area is indicated by the box in Fig. 1a. Three outstanding features appear in Fig. 2a. First, in the seashore strip in which rainfall decreases (Fig. 1a), the dominant trends for all 80 pairs are as expected, negative, and are particularly strong over the central region shown in Fig. 2a. Second, the opposite is true for the inland (second) strip in which the majority of the trends (108 pairs) are positive. Third, in the mountain strip no clear preference is found. In fact, about half of the 98 pairs show increasing trends and half show decreasing trends.

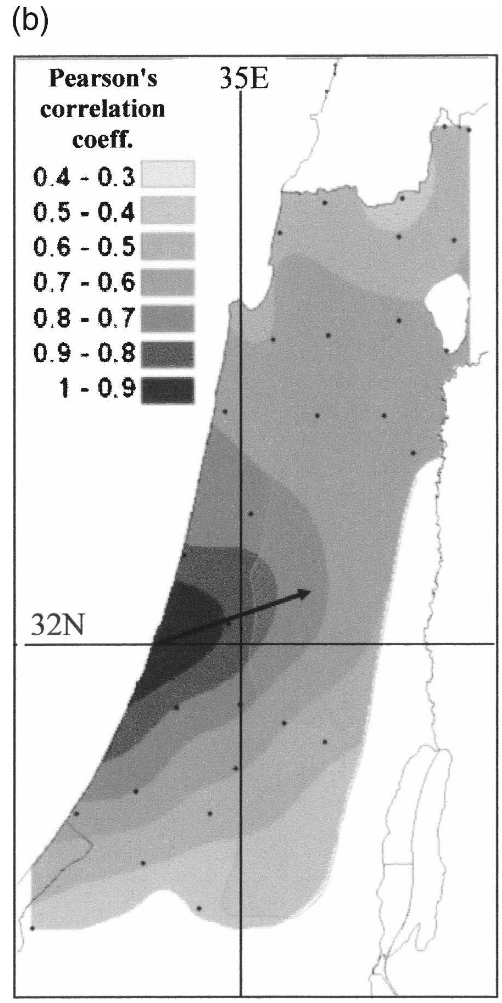
When plotting the cumulative frequency of the various trends from the most negative slope upward, Fig. 2b shows that about 50% of the stations paired with a mountainous station (line with triangles) show positive trends in the central region of Israel. Similar results were also obtained for all 799 pairs coupled with a mountain station (not shown). This is not unexpected when no real precipitation reduction of orographic rainfall exists in the observations.

5. The trends in orographic rainfall ratios: A focus over central Israel

Figure 3a shows the map of all stations employed over central Israel. Stations 7–11 are used by GR04, who considered them as seashore (named coastal in GR04), while in fact, they are all inland and located in the polluted region *downwind* of the greater Tel Aviv urban area. Stations 1–6 are seashore stations used in this study. Figure 3b shows the arrow pointing to the maximum correlation of rainfall amounts based on



Coastal stations			Mountainous stations	
used in this paper	5. Bat Yam	9 Ben Gurion airport	used in this paper	Used also by GR
1.Gaash	6.Palmahim		12. Sebastia	16. Nablus
2. Kefar Shmariahu	Used only by GR	10. Rishon Letzion	13. Jinsafut	17. Salfit
3. Tel Aviv Airport	7. Qiryat Shaul		14. Deir Istiya	18. Singil
4. Jaffa port	8. Bet Dagan	11. Zerifin	15. Deir Ghassana	



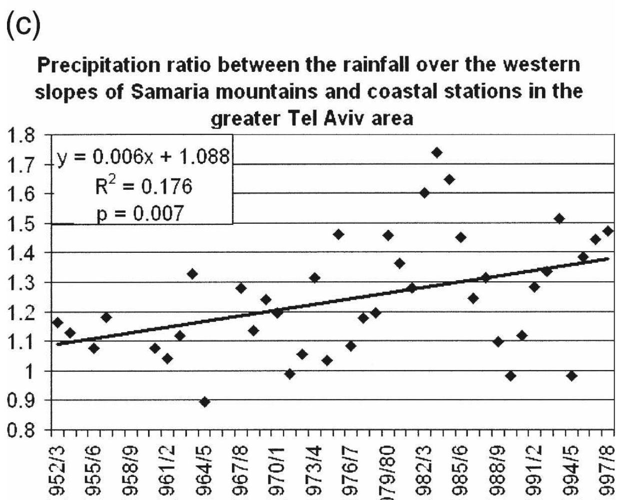


FIG. 3. (a) A map of all of the stations over central Israel used in this study. Note that stations 7–11, used by GR04, are all inland stations, while seashore stations employed in our analysis (see text) are along the coast (station numbers 1–6). The greater Tel Aviv area is shown as well as the general wind direction during rainstorms (solid arrows). In the legend, three different lists of stations are given: stations used in this paper, stations used in the GR04 paper, and stations used in both papers. The height above sea level is indicated by the shading. (b) Contours showing the spatial correlation of rain spell amounts calculated by the Pearson method. The arrow indicates the maximum correlation axis, which is affected by the mean wind direction during the rain spells. The arrow is parallel to the wind arrows in (a). The correlation coefficient values are given in the legend. This analysis is based on 419 rain spells during the period 1954–2004. (c) The annual precipitation ratios between the Samaria hills [stations 12–18 in (a)] and the central coast [stations 1–6 in (a)] clusters for the period 1952–98 are plotted along with the best-line fit. This clearly shows a significant increasing trend (r = 0.42, p = 0.007), in contrast to the results of GR04.

storm events (rain spells) analysis. Figure 3c shows the annual precipitation ratios and the best-fit line between the Samarian hills (station numbers 41, 45, 47, and 50, all located north of Jerusalem, which is station number 64) and the seashore stations (upwind of the pollution sources) during 1952–98. These results show a significant increasing trend in the orographic ratio.

The greater Tel Aviv urban area is depicted in Fig. 3a, and by considering it with Fig. 1 it becomes clear that when many of the seashore stations are replaced by stations located downwind or within the greater urban area of Tel Aviv, in which strong positive trends due to urban effects occur, a decreasing orographic ratio is obtained. Indeed, when seashore stations not affected by the urban effects are selected for the coastal cluster, a significant ($p = 0.007$) *increasing* trend in the orographic ratio R_0 is obtained (Fig. 3c).

A correct estimation of the orographic ratio requires selecting stations that are undisturbed by the topography or other inland effects as much as possible. Optimal stations for orographic ratio studies should therefore be over the seashore, for instance, and not farther inland downwind of urban areas or over the foothills of the mountains. For the definition of orographic ratio see, for example, Hill et al. (1981), Browning (1980), or Alpert (1986). Huschke (1959) defines orographic precipitation. Furthermore, if the coastal stations are selected right over the area of the maximum positive rainfall urban enhancement effects due to the thermal heat island and mechanical convection [Goldreich (2003, Fig. 12.2), also Landsberg (1981) for greater Tel Aviv urban effects], a seemingly decreasing "orographic ratio" is unavoidable. For further discussion, see section 7.

6. The trends in orographic rainfall ratios: A focus over northern Israel

a. The trends in R_0: Case of north Israel

In this section, the orographic ratio in the north of Israel is examined for the period 1951–2006. The cluster of stations chosen for this study include all of the available stations on the coast, upwind of the pollution centers, and for the mountain cluster all of the available stations on the upwind side of the water divide of the Galilee Mountains. Figure 4a is a map of the region with the altitude contours as well as the marking of the water divide. The figure also lists all of the northern stations used for the present analysis and those used by GR05. The two heavy arrows represent the computed storm direction in this area. Note that just as GR04 did for central Israel, stations 12 and 13 used by GR05 are directly downwind of the main pollution center. Furthermore, coastal stations 8–11 used by GR05 are a little north of the average path of the storms affecting the Galilee and therefore may not be as adequate for calculating the orographic ratio for this region.

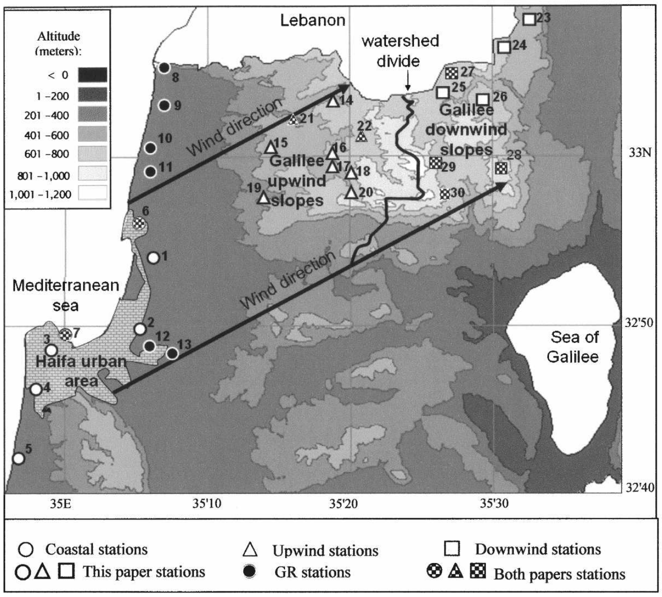
Figure 4b represents the orographic ratio between the western slopes of the Galilee Mountains against the seashore stations from 1951 to 2006; in contrast to GR05, no change can be seen in this figure.

b. The trends in rainfall ratio between the rainfall on the upwind slopes to the lee side of the mountains

One of the conclusions of GR04 and GR05 is that the orographic ratio between the rain on the upwind slopes and the coastal inland area decreased by about 20%, while the ratio between the rainfall over the lee side of the mountain and the coastal inland area increased a little. This implies that the rainfall ratio on the upslope of the mountain to that over the lee side should be negative. To test this hypothesis, Fig. 4a shows the stations used on the western and eastern slopes of the Galilee Mountains. Figure 4c shows that the ratio of the annual rainfall amounts between the western and the eastern slopes increases over the years, in direct contrast to GR05.

Although this is not the subject of the present paper, one cannot overlook the fact that these results may have direct implications for the effectiveness of cloud-seeding operations in Israel. It is important to note that the intent of the cloud seeding in the north of Israel is to increase precipitation over the target area located on the lee side of the Galilee Mountains, which is part of the catchments area of the Sea of Galilee (see Fig. 4a). In other words, if the precipitation ratio of the western to the eastern slopes increases over the years, it implies one or a number of things. 1) Cloud-seeding operations increase the rainfall on the western slopes of the mountains, something that contradicts the objectives of the project and is not observed in the present analysis. 2) Cloud-seeding operations actually decrease the rainfall in the target area. 3) Cloud seeding does not affect the rainfall in the area and the increase in rainfall on both seashore and the upslope side of the mountains (there is no change in rainfall ratio between these two areas) is a result of the urban effects of Haifa Bay. Note that the circulation pattern around Haifa Bay is complicated by the presence of the Carmel Mountain, which diverts the flow and in some cases splits the storms [e.g., Goldreich et al. (1997) with reference to surface flow]. This last possibility seems the most reasonable, because it agrees with the observed urban effects in Tel Aviv and in other areas around the world (e.g., St. Louis, Missouri; see the discussion). Of course, one cannot rule out the possibility that synoptic changes have occurred in the past 50 yr (see references below). In fact, some synoptic changes have taken place over the area, such as the significant increase in the number of Red Sea trough days over the region or the reduction in the number of rain-bearing Cyprus lows (e.g., Alpert et al. 2004), hence, the underlying GR04 and GR05 assumption of "stationarity" in climate except for microphysical changes is incorrect.

(a)



Northern coast stations		Galilee upwind slopes stations		Galilee downwind slopes stations	
used in this paper	7.Haifa Harbour	**used in this paper**	**Used also by GR05**	**used in this paper**	29. Meron
1.Kefar Masaryk	**Used only by GR**	14. Fassuta	21. Miilya	23. Yiftah	30. Amirim*
2.Qiryat Bialik	8. Rosh Haniqra	15. Yehiam	22. Hurfeish	24. Malkiyya	*Amirim station represented in GR05 as a western Galilee station although it is located in the eastern side of the divide.
3. Haifa biol. Inst.	9. Gesher Haziv	16. Kefar Makhul		25. Baram	
4..Kefar Gallim	10. Nahariyya	17. Kefar Sumei		26. Rihaniya	
5. Atlit	11. Regba	18. Peqiin		**Used also by GR05**	
Used also by GR05	12. Qiriat Atta	19. Yirka		27. Yiron	
6. Acre	13.Ramat Yohanan	20. Harashim		28. Har Kenaan	

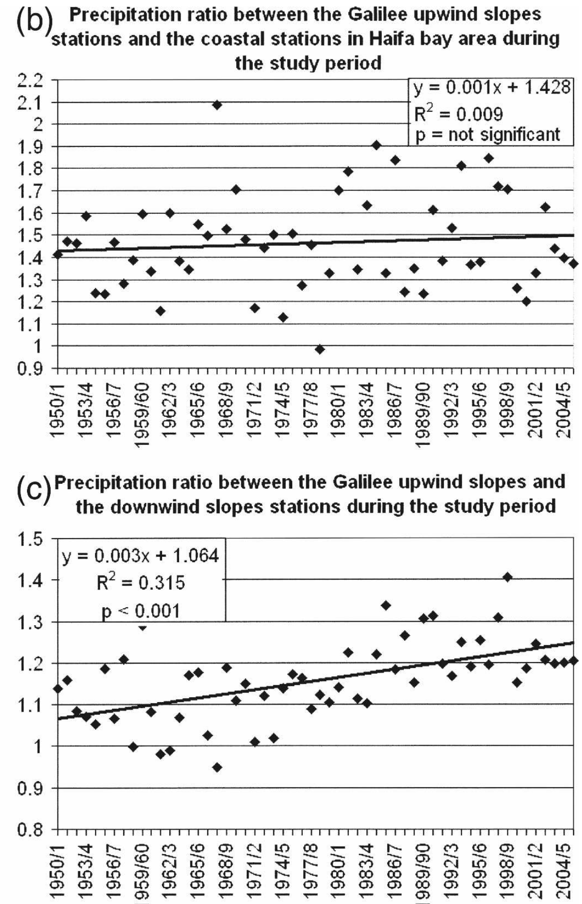


FIG. 4. (a) As in Fig. 3a but for northern Israel. The location of the Haifa urban area is marked as well as the general wind direction during rain spells. Here, a distinction is made between mountainous stations to the west of the watershed divide (Galilee upwind slopes) and to the east (Galilee downwind slopes); see text. The watershed divide is marked on the map (in Fig. 3a only stations west of or on the watershed divide were analyzed). (b) The precipitation ratios between the Galilee upwind slopes (west of the watershed divide) and coastal stations in the Haifa area for the period 1950–2006. There is no significant trend ($r = 0.01$). (c) The precipitation ratios between the Galilee upwind slopes and the downwind slopes for the period 1950–2006. The curve shows a significant increasing trend ($r = 0.56$ $p < 0.001$) in contrast to the concept raised by GR04 and GR05.

7. Discussion

Analysis of the rainfall data in Israel revealed the following. 1) There are no reductions in rainfall averaged over the 50-yr period of record in any mountain station. 2) That in the recent period there is even some *increase* in the orographic rainfall over central Israel when compared to the seashore stations (in which rainfall in some stations has decreased). 3) There is a decrease in the orographic rain ratio when mountain stations are compared to inland stations, because the increase in the inland stations was larger than the increase in the mountain stations. To estimate the orographic ratio, GR04 and GR05 consistently used stations located downwind of or within urban areas. Thus, in their case R_0 also reflects significant other urban effects along with pollution. Our study is based on seashore stations where the urban effects are minimized. In spite of the fact that GR04 argued that the orographic ratio decreased over the years, a closer look at their data from Ben-Shemen versus Kiryat Anavim (GR04, their Figs. 4a and 4b) shows similar increases in the inland stations over that in the mountains. 4) When all the mountainous stations are paired to all other stations, the number of pairs that showed increases in the orographic factor is about equal to those in which decreases were found. This points out the fact that it is always possible to select pairs of stations that have decreasing or increasing trends in R_0. To be objective, all of the stations have to be included in the analysis, as was done here.

In their abstract (second sentence) GR04 state: "precipitation losses over topographical barriers downwind of major coastal urban areas in California and in the land of Israel that amount to 15%–25% of the annual precipitation are quantified." The results of the present analysis show that this statement is absolutely wrong and misleading. The results also suggest that, at least in Israel, if pollution has any effect on annual precipitation, it is a positive effect. On the other hand, it is more probable that other factors such as the urban heat island, urban moisture, and roughness etc. could play a much more important role as discussed at length in many urban studies (see below), while completely ignored by GR04 and GR05.

As to the rainfall orographic ratio, R_0, trends over south Israel discussed by GR04, our analysis shows that the temporal rainfall increases over the southern coastal plain are larger than those over the mountains. The increases over this region (northern Negev and south coastal plain) were extensively studied and were proposed to be due to both intensive land-use changes and synoptic changes (some urban effects related to the Gaza area cannot be neglected as well) in the last 50 yr (e.g., Ben-Gai et al. 1998; Steinberger and Gazit-Yaari 1996; Alpert et al. 2004) and were affirmed recently with extension of the data to 2004 by Yosef (2007). Hence, again, the orographic ratio R_0 seems to be decreasing if all of these effects are ignored as was done by GR04.

Furthermore, even when disregarding the wrong selection in the coastal stations, there are two other mathematical principles ignored by GR04 and GR05. A decrease of any ratio, such as R_0, could be the result of either increases in the denominator or decreases in the numerator. We show that since the increases over the inland coastal stations are larger than those over the mountains as shown in Fig. 1a [also in GR04, their Figs. 4a and 4b; same applies to the study in Denver by Jirak and Cotton (2006), their Figs. 2a and 2b, and in China by Rosenfeld et al. (2007), their Fig. 3a], the R_0 definitely decreases, but not because of precipitation suppression on the mountain but because of increases in precipitation downwind of the city, possibly due to urban heat island effects (or other long-term changes in synoptic processes possibly linked to climate change). Such increases in precipitation over regions downwind of large urban areas are well-known urban effects as discussed by Dabberdt et al. (2000) for summer urban areas in the United States; by Changnon et al. (1971) and Changnon (1980) for St. Louis, Missouri; and by Goldreich and Manes (1979), Goldreich (2003), and Shafir and Alpert (1991) for winter rainfall over areas downwind of the greater Tel Aviv region and Jerusalem. These urban effects include the heat island, roughness, humidity, and so on, as well as various aerosol effects. As shown here (Figs. 2 and 3) when selecting a cluster of stations on the seashore, upwind of the large urban areas, the orographic ratio indeed increases, in contrast to the claims by GR04. Furthermore, the stations selected by GR04 are located right over the area of the maximum positive rainfall urban effect of greater Tel Aviv, suggested to be primarily the result of the thermal heat island and mechanical convection (Goldreich 2003, Fig. 12.2; Landsberg 1981). It is very relevant here to note that on the same map of the aforementioned urban residual rainfall, the residuals over the seashore (where our coastal stations were chosen, as required in a proper orographic ratio study, i.e., stations 1–6; see Fig. 3) are nearly zero, confirming that the selection of seashore stations is correct for such a study. The urban residual was calculated by first developing multiregression maps of the rainfall over Israel using four geographic factors (latitude, distance from the sea, altitude, and the rain shadow). The fifth factor is the urban effect estimated by the residuals. At the second stage, the differences between the observed climatic 30-yr rainfall averages and the multiregression values are defined as the rainfall residuals. For further details on this method for calculating the urban residual, see Goldreich (2003).

Our analysis of the orographic ratio in northern Israel has shown no change over the years of the study. This is in contrast to the study by GR05 who argued that this ratio decreased. Furthermore, we reveal that the ratio of the rainfall in the western slopes over the eastern slopes of the Galilee Mountains increased over the years, because of increases in rainfall amounts on the western slopes. The reasons for the increase in the orographic ratio over the western slopes is possibly due to cloud seeding, the urban heat island, or changes in the synoptic conditions.

Since the target area for the seeding project is on the eastern slopes of the Galilee Mountains, it is more probable that the urban heat island or synoptic larger-scale effects are the dominant factors in increasing this ratio and that seeding had no effect on the evaluated target area. It does not rule out, however, the possibility that seeding increases the rainfall downwind in the Golan Heights, but this has to be evaluated separately.

Another important principle is based on a very basic mathematical rule: Any ratio B/A decreases if one adds a constant D on both the nominator and the denominator. The reduction of the ratio can then be approximated by $(D/A)(1 - B/A)$ (see the appendix). In fact, the decrease in the ratio erroneously calculated for central Israel by GR04 fits well into this formula.

Orographic rain over complex topography very often suffers from very high variability (e.g., Alpert et al.

1994). Hence, nearby stations may have very different characteristics as illustrated, for instance, by Alpert and Shafir (1991) in reference to Hill et al. (1981) and their suggestion for a general function for the orographic ratio enhancement dependence on low-level wind intensity. This illustrates the high sensitivity to the selection of mountain stations and their position relative to the local horizontal wind vector impacting the mountain. The convective-type rain that falls over Israel leads to high variability in the coastal rain as well. Here, we have demonstrated how different clusters of stations over orography and the coast can yield opposite, yet still significant results.

From all of this, we conclude that the evidence shown in Israel suggests that other factors besides aerosols are predominant in defining the trends in the orographic rainfall ratio. Hence, there is no evidence of any suppression of rainfall over the mountains due to pollution.

8. Summary

In this paper the trends in the orographic rainfall ratio R_0 over Israel are reanalyzed. It is shown that the rainfall has not changed much over most of the mountain stations. The average rainfall changes over the mountain, inland, and seashore strips are 106%, 108%, and 105%, (109%, 109%, and 103% for the central region only), respectively. The overall evaluation of the orographic ratio R_0 calculated by taking the ratio of each mountain station against all of the other seashore and inland stations indicates that about 50% of all pairs show a positive trend in R_0.

We find R_0 to be highly sensitive to the selection of the stations upwind of the mountain. The correct definition of R_0 requires, in the Israeli case, the use of a seashore cluster of stations. If some of the seashore stations are replaced by inland stations and in particular stations that are over the region of potential positive rainfall urban enhancement due to the thermal heat island or other urban effects (as was done in GR04 and GR05), a seemingly decreasing "orographic ratio" is unavoidable. In such a case, urban dynamical positive effects on coastal rainfall can be erroneously interpreted as pollution suppression of orographic rainfall (e.g., GR04 and GR05).

When seashore stations are selected, as required by a proper definition of the orographic ratio, increasing R_0 is obtained over central Israel or an insignificant trend over the north.

It is also shown that not only do the results depend on the choice of stations for the analysis, but that the decrease in the ratio could be obtained even if the amount of rain increases by the same amount in both the seashore and mountain clusters (see the appendix). We found that the rain in the central seashore stations actually decreased, so that the ratio between the mountain and seashore actually increased. Taking the ratio between the mountain and the inland stations leads to a decrease in the value, but not necessarily due to any suppression in the mountain but potentially due to an increase in the inland stations, caused by the urban heat island effect (e.g., Goldreich and Manes 1979; Goldreich 2003).

Furthermore, evaluation of the ratio of rainfall on the west to the east side of the water divide in the Galilee Mountains (in the north) exhibits an increase over the years; this is an opposite trend to the one expected based on the analysis of GR05. This observation is very important in terms of the effects of operational cloud seeding in the north of Israel. The target area of the Israeli operational seeding project is located downwind of the water divide in the Galilee Mountains. The present results suggest that the rainfall in this region has decreased as compared to that on the upwind side of the mountain. This could be a result of a number of factors such as a negative effect of seeding (seeding decreases rather than increases the rain at the target area), or a general increase of rain around the urban area including in the upslope part of the Galilee Mountains, or general changes in the synoptic conditions in the past years. This important point will be discussed in another paper.

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APPENDIX

The Mathematical Rule Dictating Orographic Ratio Decreases over Regions with Homogenous Increases of Rainfall

Take $R_0 = B/A$ as the ratio of the mountain rain B and the coastal rain A. Then add the same amount of rainfall in both A and B, say the amount D; then $(B + D)/(A + D)$ decreases relative to B/A. (The opposite is true, i.e., the ratio increases, when the rainfall decreases by D.) When substituting the approximate values for $B = 666$, $A = 450$, and $D \approx 150$ based on the GR04 example for the Kiryat Anavim versus Ben-Shemen stations over central Israel, one obtains for the starting ratio (i.e., 1920) $R_0 = A/B = 1.48$. For the ending ratio in 2000, GR04 got 1.24. When substituting $B = 666$, $A = 450$, and $D \approx 150$, one obtains the corresponding R_0 values of 1.48 and 1.35. The reduction of the orographic ratio can be expressed by the formula

$$\Delta R_0 = (B + D)/(A + D) - B/A,$$

which can be approximated when $D < A$ by

$$\Delta R_0 = (B/A + D/A)\,(1 - D/A) - B/A$$

or further approximated to

$$\Delta R_0 = (D/A)(1 - B/A).$$

This ΔR_0 value is always negative in regions with increasing rainfall, $D > 0$, and an orographic ratio larger than 1, that is, $B/A > 1$. This formula leads, for the aforementioned B, A, and D values, to a slope of $-0.16/(80\text{ yr}) \approx -0.002$. It is not surprising to find that this calculated slope is very close to the value obtained by GR04 in their Fig. 4d, that is, a slope of -0.002, for the same two stations since in both stations (Kiryat Anavim and Ben-Shemen) the rainfall increased by approximately $D = 100$–150 mm.

An interesting conclusion from this mathematical rule follows. In *every* orographic region in the world with a homogeneous rainfall increase due to some large-scale process acting on both low-level and mountainous regions (or from any other reason independent of the orographic factor such as global warming, which enhances the hydrological cycle), the R_0 graphs should decline according to the values given by A, B, and D and the derived formula.

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