Rainfall Anomaly over the Lee Side of Mount Carmel (Israel) and the Associated Wind Field

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ABSTRACT

Yagur and other rain gauge stations located on the lee side of Mount Carmel in Israel experience much higher amounts of precipitation than those measured on the windward side of the mountain at a similar altitude and more rain than stations on the mountain itself. This phenomenon is consistently observed, and in the current study it is investigated primarily by means of simultaneous rain–wind observations and by using a two-dimensional simplified orographic model. Orographic model simulations suggest the existence of a flow disturbance at the lee of Mount Carmel, which might cause local rain enhancement. Results from the anemograph placed at Yagur, along with other wind measurements in the Carmel region, support the findings of this model. Observations depict the disturbed flow that occurred at the lee of Mount Carmel and was associated with rain enhancement. The channeled flow caused horizontal convergence, which is in accordance with the second hypothesis. Observations during the rainy periods indicate that the rain enhancement in Yagur is associated with the ridge-parallel flow on the lee side of the mountain. It is hypothesized that the horizontal convergence of the leeside flow with the flow over the mountain causes the local enhancement of precipitation.

1. Introduction

The term rain shadow, which is attributed to the rainfall decrease in the lee side of a topographic obstacle in various climatic and topographic scales, is a well-known phenomenon. The maximum of the orographic precipitation that falls on the upwind side is often recorded somewhat downwind, beyond the summits (e.g., Barry and Chorley 1987). However, in certain topographic or synoptic conditions the lee side may receive a substantial rainfall depth (e.g., Smith 1979). One such seemingly anomalous behavior occurs at Kibbutz Yagur.

Yagur and other rain gauges on the lee side of Mount Carmel in Israel (Fig. 1) experience much higher amounts of precipitation than stations on the windward side of the mountain at a comparable topographical height. Yagur, located at a height of only 30 m above sea level, receives even more rain than rain gauges on the mountain itself, on the windward side, at altitudes of 300–400 m above sea level. The anomaly occurs both with daily (arbitrary dates chosen) and average annual precipitation amounts (Tables 1a,b). This anomaly of Yagur is consistent and has been discussed for some time.

Ashbel (1968) was probably the first who tried to explain this anomaly: he conjectured that the increase of precipitation at Yagur was due to advection. In this explanation, westerly and southwesterly winds, the rain-bearing winds in Israel, encounter Mount Carmel and are forced to climb and cross the mountain ridge. Because of inertia, the winds do not descend immediately on the east side of the mountain (the lee side) but continue to rise after reaching the peak. As a result, this explanation postulates that Yagur should receive more precipitation than expected for its altitude. Katsnelson (1968) explained the anomaly in a similar manner.

Relevant to the advection hypotheses, Hovind (1965) found, by means of rain observations, and Poreh and Mechrez (1984), by simulating raindrop motion, that under the conditions of strong winds, raindrops can indeed be advected over the ridge and fall over the lee slope. However, these studies dealt with small-scale topographical configurations, relatively short horizontal distances (order of few meters), and very steep slopes, which do not fit the scale of the Carmel.

Sharon and Arazi (1993) gave additional examples where rain gauges at the lee of the mountain enjoyed similar rainfall advantages over the mountain rain gauges. Using a numerical model, they investigated rain and

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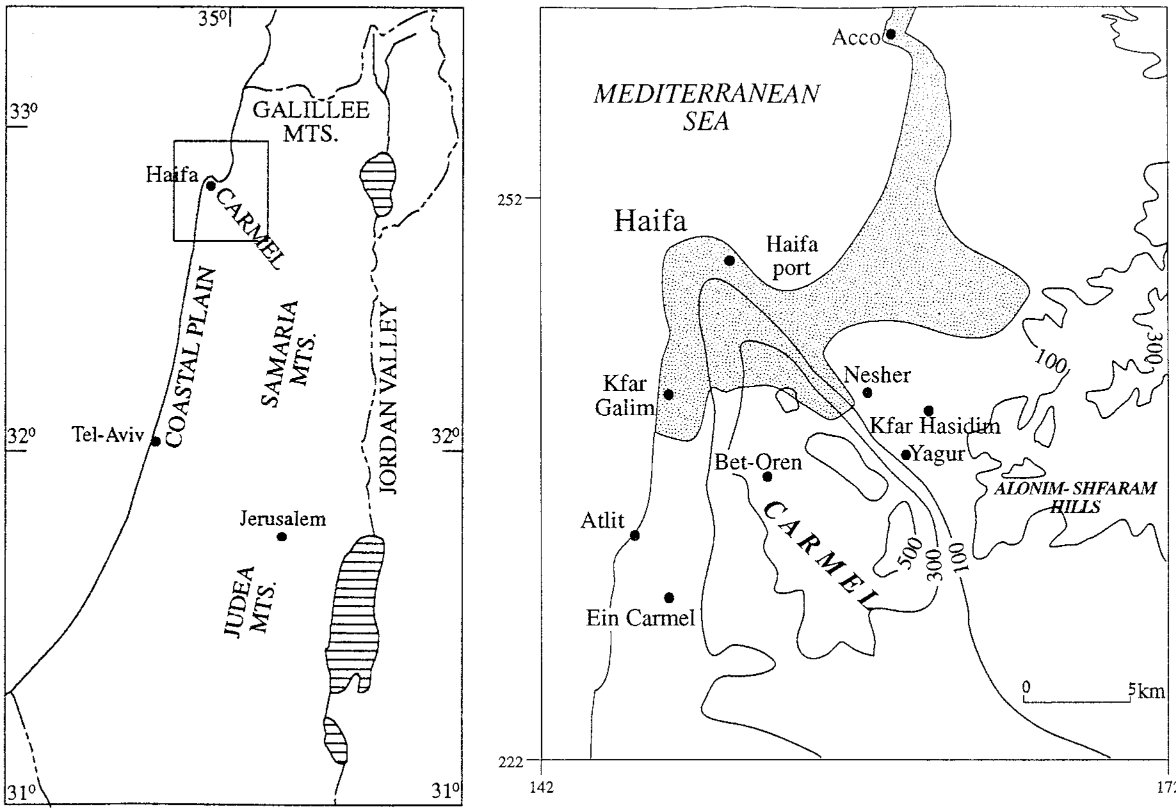


FIG. 1. (a) The general location of the study area. The square indicates the study area of Mount Carmel. (b) The study area with local grid (kilometer distance) values. Contours are at 200-m interval. Shaded area represents the urban–industrial area of Haifa conurbation.

wind fields for a given topography. Their findings indicated the existence, under certain conditions, of an eddy over the lee slope that might redistribute raindrops and create positive and negative anomalies in comparison to the orography effect. Consequently, Sharon and Arazi tried to explain the rain anomalies mentioned before with the "eddy hypothesis." His empirical study considered a relatively small horizontal scale and may therefore not reflect the Yagur situation.

Forchgott (1949) and Alaka (1960) mentioned that lee waves with a reversal branch flow on the upstream on the lee side or lee eddies might significantly change airflow at the lee of mountains. Others (Wallington 1960; Atkinson 1981) have pointed out that lee waves could cause strong vertical airstreams, accompanied with orographic clouds. However, precipitation over the lee of mountains, due to lee-wave activity, is not a frequent phenomenon (Summer 1988). A preliminary browse of Yagur and other "lee stations" rainfall data versus some upwind rainfall stations (Freundlich 1994, unpublished M.A. thesis) showed that rain enhancement at Yagur is quite frequent and occurs during most rain events. Furthermore, lee waves or lee eddies more typically occur in weather conditions of high static stability in the lower layer of the troposphere (Atkinson 1981), and it is not likely that these are the conditions of rain days in Israel.

More closely related to the Carmel anomaly is probably the recent work on continuously stratified flow past isolated 3D obstacles (e.g., Smith 1980; Smolarkiewicz and Rotunno 1989). With the Carmel height of about 500 m, the upstream wind of 10 m s^{-1}, and the Brunt–Väisälä frequency of $N = 0.01$ s^{-1}, the Froude number

TABLE 1a. Annual average precipitation amounts over both sides of Mount Carmel for the period of 1931–60.

	Coast		Mountain	Lee	
	Ein Carmel	Atlit	Bet Oren	Yagur	Kfar Hasidim
Altitude (m)	20	10	370	30	15
Rain (mm)	534	484	686	689	641

TABLE 1b. A rain spell case example of precipitation amounts (mm) on both sides of Mount Carmel.

Date	Coast Ein Carmel	Mountain Bet Oren	Lee Yagur
31 January 1988	9.7	17.0	20.7
1 February 1988	55.0	42.0	71.2
2 February 1988	3.5	5.0	3.5
Total	70.2	64.0	94.5

(Fr = U/Nh) is about 2, suggesting that Smith's (1980) linear theory may be relevant. For this range of Froude numbers, the flow *around* the mountain is—according to theory—quite important, although, for Froude numbers, less important than the flow *above* the mountain. The elongated shape of the Carmel and the surrounding topographic complexities do not allow further estimation from the theory for symmetric bell-shaped obstacles.

In contrast to theory, there are a number of observational and modeling studies that indicate rainfall enhancements at the lee of mountains (e.g., Banta 1990). Of particular interest is the radar climatology by Kuo and Orville (1973) over the Black Hills of South Dakota showing maxima in echo frequency over the northeastern and southeastern lee sections of the hills during summer. They explained these maxima by convergence of airflow from the southwest and northwest, respectively, with upslope motions over the heated sloping surfaces. Although the Kuo and Orville study refers to summer rainfall, their proposed mechanism seems similar to ours. Other studies over elongated mountain shapes also seem to support the converge hypothesis for the Carmel.

There seems to be some scaling confusion in the published literature about the potential sources for enhancement or weakening of rainfall in the lee of mountains. Some mechanisms such as lee depressions (e.g., Genoa depression) clearly support rainfall enhancement, while others like rain shadow or sheltering favor diminished rainfall at the lee of mountains. In addition, there are other mechanisms such as lee waves that may have both positive and negative contributions depending on distance, stability, etc. Table 2 is a preliminary suggestion for grading the various mechanisms along with their scale and potential contribution as deduced from the literature. The table demonstrates how complex it may be to associate lee rainfall change with a specific physical mechanism. The scale of the phenomenon may be, however, helpful in identifying the dominant forcing.

In the present study, we examined one additional hypothesis that may explain the Yagur anomaly: airflow channeling (a general term for confluence/diffluence) due to topography. Northwesterly winds (280°–320°) that hit Mount Carmel on rainy days diverge into two directions: one is channeled parallel to the mountain (320°), into the valley that lies to the lee of the Carmel, and the other flow continues to climb over the upwind slope (western slope; 270°). The two flows seem to converge over the lee side of the Carmel to cause rain enhancement at Yagur.

A brief background on the area of research and a description of our analysis methods are presented in sections 2 and 3, respectively; section 4 describes the results of this study, and section 5 considers their implications for the several hypotheses. Three case studies of individual rain events are analyzed in section 6, while section 7 presents summary, conclusions, and suggestions for subsequent research.

2. Physiography

Extratropical cyclones reach Israel mainly during the winter months and less during the transition seasons, with showers along the cold front (and in the cold air mass that follows this front) being the typical precipitation that is predominantly convective. Some 65% of the annual rainfall occurs during the 3-month period of December–February. During the summer months (June–August), any precipitation at all is a very rare event. In this respect, Israel experiences the extreme case of the Mediterranean climate. Snow is uncommon, and if it occurs it is generally confined to the tops of the hills.

The Carmel, an extension of the mountains of Judea and Samaria, is a hilly region in northwestern Israel (Fig. 1a). The Carmel ridge extends generally along a southeast–northwest axis, with relatively gentle slopes to the southwest and rather sharp slopes to the northeast. The highest peaks of the Carmel reach an altitude of more than 500 m, but a significant portion of the Carmel does not rise above 300 m. The total width of the Carmel ridge is about 15–25 km, where the horizontal distance from peak to mountain foot is 10–20 km upwind (western slope) but only 2–4 km downwind (eastern slope). Because of its proximity to the sea, the Carmel is one of the rainiest areas in Israel: its highest portions receive more than 700 mm of rain a year. Usually, the general direction of the wind in the area on rainy days is southwest to west (225°–270°), but the wind may blow from a wide spectrum of other directions. The dominant westerly direction for the Carmel rainfall and other characteristics are found already in the Biblical rainfall forecast by the prophet Elijah as discussed by Alpert (1984). The study area is bracketed by longitudes 142° and 172° and latitudes 222° and 252° in Israel's grid (Fig. 1). In this area of 30 km $\times$ 30 km, there are some 50 rain gauges, but only 12 of them are on the mountain itself.

3. Methods

The current study examines the plausibility of the different hypotheses for explaining the anomaly at Yagur using two basic approaches.

1) Orographic 2D Alpert and Shafir (1989a) model based on mechanical uplift by the mountain slopes. The model parameterizes the advection effect.
2) Simultaneous rain and wind observations.

a. The orographic model

The orographic model used is a 2D horizontal model that follows 2D topographical slopes. The model, an elaboration of Alpert's (1986) formulation, was developed by Shafir (1988) and Alpert and Shafir (1989a).

TABLE 2. A preliminary scaling of leeside atmospheric phenomena and their role in enhancement (+) and decreasing (−) of precipitation. Some of these phenomena occur for scales beyond those suggested in the table. The suggested scales are those that are more frequently associated with the pertinent phenomena.

Phenomena scale	Rossby waves	Lee depression	Lee vortex	Shadowing	Lee waves	Channeling	Lee eddy	Advection
Macro- α	+							
10 000 km								
Macro- β	+							
2000 km								
Meso- α		+	+	−				
200 km								
Meso- β		+	+	−	+ −	+ −		
20 km								
Meso- γ				−	+ −	+ −	+	+
2 km								
Micro- α						+ −	+	+
200 m								
Micro- β						+ −	+	+
20 m								
Micro- γ						+ −	+	+
Reference	1	2	3	4	3	5	6	7

1) Holton (1992).
2) Klemp (1992).
3) Atkinson (1981).
4) Barry and Chorley (1987).
5) Alpert and Shafir (1991).
6) Sharon and Arazi (1993).
7) Alpert (1986).

They tested the model in the Judean and also in the upper Galilee Mountains in Israel and obtained good correlations between modeled and observed rainfall. The basic assumptions of the model are that the convergence of moisture at the boundary layer of the mountain approximately equals the precipitation that falls on the mountain and that the convergence causing orographic rain is determined only by the geometrical uplift of the mountain. The model requires following input parameters: the wind speed, vertical lapse rate of the temperature, gradient of relative humidity, and upwind precipitation. For this study, we assumed that there is no negative orographic effect, and correspondingly negative topographical slopes were treated as zero by the model (see Shafir 1988).

An advection parameter was introduced into the model in order to simulate the advection of clouds by the wind, with the assumption that during rainfall clouds are advected by the wind and therefore they precipitate some distance downwind from the point of their origin. The advection parameter is determined by the processes involving orographic rain, that is, the horizontal wind velocity and typical lifetime scale of precipitating cloud, and it can be adjusted. In principle, a small advection parameter causes large differences in simulated precipitation between neighboring points (showing a strong effect of topographical perturbations), whereas a large advection parameter has a smoothing effect, reducing the differences between the points. The effects of the advection parameter on precipitation are illustrated in Figs. 2a,b. A detailed description of the model can be found in Alpert (1986), Shafir (1988), and Alpert and Shafir (1989b).

Obviously, a 3D model run should be the ultimate goal in such a study in order to clarify the exact role of topography through sensitivity experiments. However, as discussed by Alpert et al. (1994), mesogamma-scale modeling of precipitation is still not easy to handle. It requires extensive computing resources that are not yet available for testing the Carmel–Yagur case where the appropriate horizontal resolution is about 1 km.

To operate the 2D model, a topographical height matrix was constructed, based on a horizontal grid interval of 1 km. The model rain formulas were solved numerically over the grid covering the study domain. Typical parameters for average rain conditions in the research area (see Table 3) and the exact topography of the area were used as input. Model simulations were tested by comparing the spatial distribution of observed rainfall with the model predictions.

b. Wind directions during rain spells

The basic assumption of the current study was that wind direction significantly affects the rainfall distribution over both flanks of the Carmel. We therefore checked the distribution of the wind during rainfall using simultaneous observations from rain and wind recorders. Three sets of observations were established. In the first set we checked the climatological mean wind direction during rainfall using a single station (Acco) over the relatively long period of 1980–91. Acco was

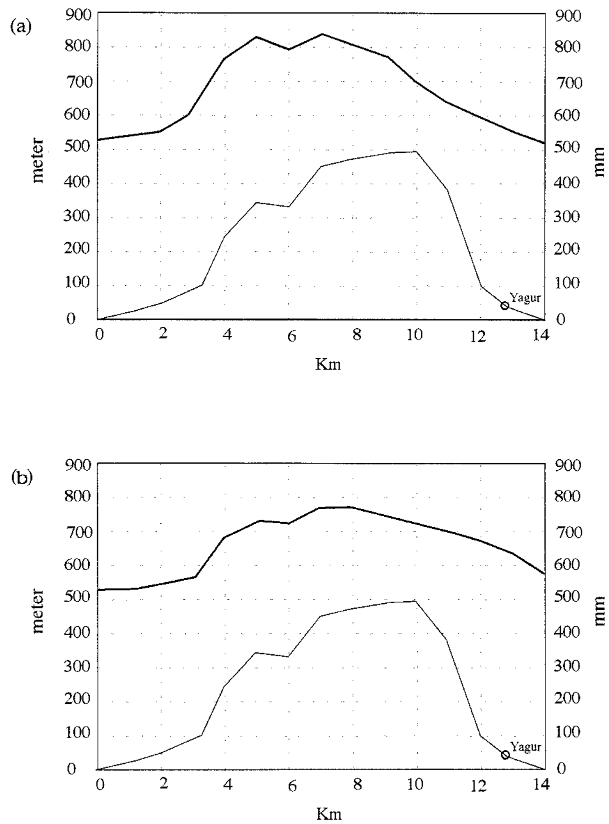


FIG. 2. Precipitation depth (thick lines) simulated over a west–east cross section of the Carmel (a) with a small advection parameter and (b) with a large one.

TABLE 3. Model input parameters for the various experiments. The basic simulation used the parameters $\alpha = 270$, $\sigma = 4$, ef $= 0.0875$, $P_0 = 513$, and the assumption that there is no decrease of the relative humidity along the west–east and the north–south axis (α represents wind direction, σ is the advection parameter, P_0 is the observed precipitation upwind and ef is an empirically determined factor representing precipitation efficiency, which serves as a tuning parameter).

Experiment period	Average rainfall period (days)	Rainfall efficiency (ef)	Wind (°/m s^{-1})	Upstream precipitation P_0 (mm)	MSL temperature (K)
1931–60	54.5	0.0875	270/10	513	291
		0.0750	260/10		
		0.0600	240/10		
		0.1000	225/10		
			220/10		
			200/10		
			180/10		
1951–80	54.5	0.0875	270/10	566	291

Lapse rate (°C km^{-1})	Gradient of relative humidity in the study domain along the axis: North–south	West–east	Vertical	Relative humidity upwind	Advection parameter (σ) (km)
−6.5	0	0 −15%	0	100%	4–10.5 (intervals of 0.5 km and 15, 20
−6.5	0	0	0	100%	4 km

chosen because it is located on a plane at a relatively large distance (about 20 km) northeast of the Carmel ridge, and so we assumed that its wind direction is unaffected by topography and could therefore represent the general synoptic flow of the entire research area. In the second set of observations we checked the average spatial wind flow distribution of the area using three wind recorders (Acco, Ein-Carmel, and Yagur; see Fig. 1) over a single season (the winter of 1992/93). In addition, we chose three incidents of heavy rain (from the winter of 1992/93) and established a detailed hourly follow up of the wind flow during the rainfall. The three sets of observations will be referred to as set number 1, 2, and 3, respectively.

Since sets numbers 2 and 3 were of a relatively short period, we compared the wind rose of Acco 1980–91 with that of 1992/93 and found no significant difference between the samples [other characteristics of the two samples were compared as well, yielding similar results; see Freundlich (1994)]. We therefore concluded that the sampling of 1992/93 is reasonably representative of the local climate. In all sets of observations, rain days were sorted into ‘‘positive enhancement days’’ and ‘‘negative enhancement days.’’ Positive enhancement days were defined as days where rainfall amounts measured over the lee side of the Carmel significantly exceeded (by at least 20%) the amounts measured over the windward side. Similarly, days of negative enhancement were days during which the lee of the Carmel received less (by at least 20%) rain than the windward side [for further information of the data collected, see Freundlich (1994)].

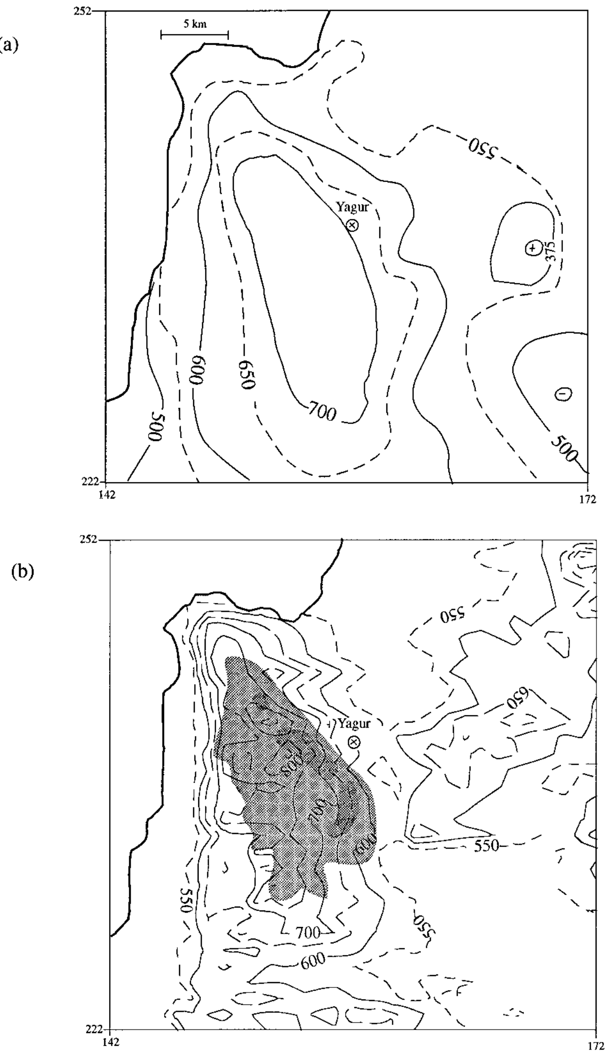
4. Results

a. Results based on the model

A comparison of the observed average annual precipitation (Fig. 3a) based on about 50 rain stations, with model simulations (Fig. 3b) with over 900 grid points, showed simulated amounts that are slightly higher than the observed values over most of the area. Assuming a wind direction of 270°, the average model excess was +2.16%, while it was 4.99% for a direction of 225° [for simulation results with other wind directions, see Freundlich (1994)]. The prominent exceptions occurred at the lee stations Yagur and Kfar-Hasidim (Fig. 1), where the modeled amounts were considerably lower than the actual precipitation (by 14%–15%). Correlation coefficients between observed and simulated rainfall totals consistently increased when these two stations were omitted. This relationship does not change, even when the model's advection parameter is increased significantly. This indicates that the model results, even with the advection parameter, do not effectively represent the Yagur anomaly. Thus, pure linear advection does not seem responsible for the Yagur precipitation excess.

(a)

(b)



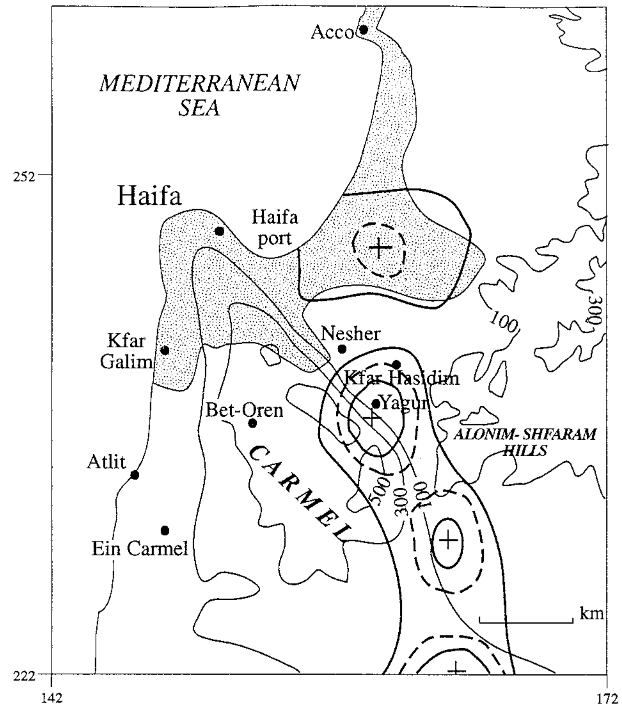


FIG. 3. Rainfall maps of the Carmel region: (a) observed rainfall normals (1931–60), (b) the model-simulated rainfall map [elevation higher than 300 m (bright) and 500 m (dark) are shaded], and (c) rainfall residuals [observed (a) minus simulated (b)]. [Rainfall intervals are 25 mm (dashed line) and 50 mm (solid line).]

The residuals map (Fig. 3c) represents the difference between observations and model prediction. It shows four significant areas of positive residuals that received more precipitation than the model predicted. The northern one is the dense urban and industrial area of Haifa Bay and its vicinity. The residuals in this area may be due to an urban influence on the precipitation, an effect not taken into account by the model. The other three areas of positive residuals were all located on the lee side of Mount Carmel. Note that the model considered negative topographical slopes as zero and assumed that there is no decrease in the relative humidity along the west–east axis over the study domain. We would have expected, therefore, that the model would predict rain quantities greater than observed on the lee side of the Mount Carmel. This, however, was not the case and further emphasizes the anomaly on the lee side of the Carmel.

It should be mentioned that the advection parameter, simulating the precipitation advected from the ridge, does, indeed, predict some excess rainfall at the lee of the Carmel, as compared with upwind stations. For example, model predictions reached values of 550–580 mm for the lee stations (Yagur, Kfar-Hasidim), as opposed to an average of 525 mm at the upwind stations at a similar topographical altitude (see Figs. 2a, 3b). However, model simulations could explain by advection only up to 73% of the actual observed enhancements (see Table 4). The simulation with wind direction of 225° gave the best correspondence to observed enhancements.

b. Results based on the observations

Analysis of the wind rose of Acco 1980–91 (set 1) revealed that the general synoptic flow during positive enhancement days tended to be mainly southwesterly as opposed to completely different directions on regular days (see also Freundlich 1994, unpublished M.A. thesis). Results received from the observations of set 2

TABLE 4. Annual average enhancements predicted by the model in comparison to the actual enhancements: d and D represent the predicted and observed enhancements, respectively; d/D is the portion of the observed enhancement that is explained by the model. Precipitation of the lee side is from Yagur and Kfar Hasidim. Precipitation of the coast is from Kfar Galim, Atlit, and Ein Carmel.

Wind direction (α)	Advection parameter (km)	Precipitation predicted over the lee side (mm)	Precipitation predicted over the Carmel coast (mm)	Computed enhancement (d)	d/D
270°	4	565.8	525.4	7.69%	24.8%
	6	609.0	522.5	16.10%	53.4%
	8	640.6	521.3	22.86%	73.7%
225°	4	590.7	524.7	12.58%	40.6%
	6	622.5	521.5	19.36%	62.5%
	8	639.1	520.0	22.90%	73.9%
180°	4	519.3	517.0	0.45%	1.5%
	6	547.2	520.5	5.15%	16.6%
	8	562.0	522.0	7.68%	24.8%
Observed precipitation		Lee: 665.0 mm	Coast: 507.3 mm	Observed enhancement: $D = 31\%$	

(spatial distribution of wind flow) showed that on enhancement days the local winds on the western side of the mountain (upwind) tended to be mainly southwesterly to westerly, whereas at the lee of the Carmel, the frequent local winds were, exclusively, northwesterly or southeasterly (Fig. 4a). In contrast, negative enhancement days were characterized by the same wind directions on both sides of the Carmel, usually southeastern (Fig. 4b).

Another important finding from the observations of set 2 was the surprising accordance between the wind rose of Yagur (current study) and Haifa-port (Atlas of Israel 1963): at both stations the most frequent directions during rainfall spells were southeast and northwest

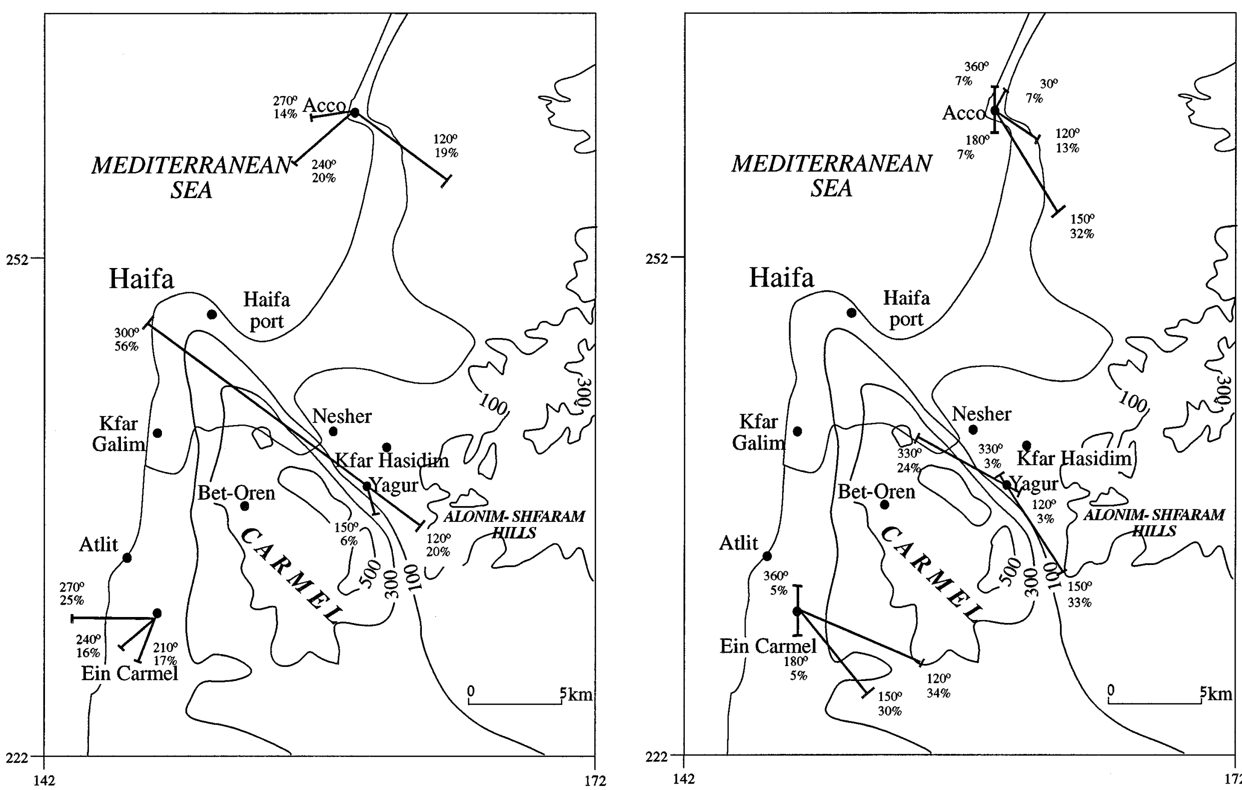


FIG. 4. The three most frequent wind directions (percentage) during rainfall (1992/93 observations): (a) on positive enhancement days, (b) on negative enchancement days.

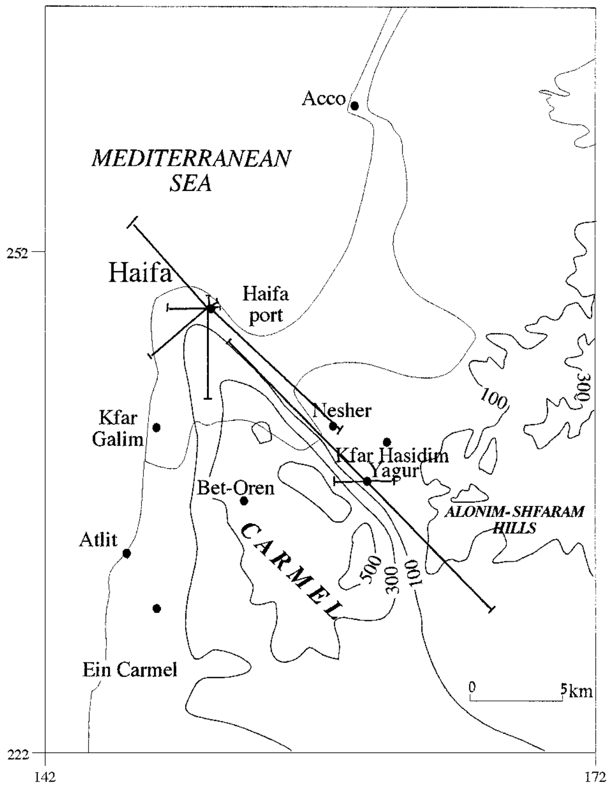


FIG. 5. Haifa and Yagur wind roses during rainfall for the 1992/93 rain season.

(Fig. 5). Note that the Carmel ridge is aligned along a northwest to southeast axis and that Haifa-port is also located, to some extent, in the lee of the Carmel.

The observations of set 3 (three case studies of rain events) revealed that the wind can sometimes blow, simultaneously, from completely different directions on the two sides of the ridge. Two main flow patterns were found typical to enhancement days. One flow pattern is characterized by southwesterly winds upwind of the western slope, together with southeasterly winds east of the mountain (Fig. 6a) blowing roughly parallel to the topographic contours. The other pattern shows western winds upwind, together with northwesterly winds at the lee of the mountain (Fig. 6b). On negative enhancement days wind directions were uniform throughout the region, being mainly from the southeast. However, some cases with uniform wind direction, but from the northwest (direction suitable for advection), were discerned.

5. Discussion

Before discussing the various hypotheses concerning the Yagur anomaly, one has to consider an urban effect. A probable urban effect on the enhancement of rainfall in the downwind of urban areas in Israel has been previously suggested for the greater Tel Aviv area (Goldreich 1981, 1987, 1988, 1990, 1995; Goldreich and Manes 1979), for the Haifa conurbation (Goldreich 1995; Goldreich and Gadoth 1989; Goldreich and Kaner 1991), and for Jerusalem (Shafir and Alpert 1991). Since the urban–industrial area of Haifa Bay is located northeast of Yagur, a dominant wind blowing from that direction should, therefore, support the urban effect. However, the results of the wind observations of 1992/1993 (Fig. 4a) indicate an enhancement at the lee of the Carmel during southeasterly circulation at Yagur, a finding that is not compatible with an urban effect. Furthermore, one would expect urban influence on precipitation to increase over the long term as the city grows. However, precipitation data of Yagur actually show a trend of slight decrease over time (though not significant), which contrasts with the positive trend found at the control station of Atlit during the same time period. Therefore, the urban effect is not a major factor in Yagur area precipitation.

a. *The advection hypothesis*

The moderate topography of the Carmel allows wind advection from any direction that cuts across the ridge that extends 140°–320°, with the most pronounced effect of advection taking place when the wind is perpendicular to the mountain (southwesterly). The dominance of southwesterly synoptic flow during enhancement days, as seen from the observations of Acco 1980–91, is therefore consistent with the advection hypothesis.

On the other hand, the orographic model suggests that advection does not fully explain the rain enhancement in Yagur. Further, we found in cases of uniform wind throughout the region that negative enhancements occur even when the winds were from directions suitable for advection. It seems, therefore, that simple horizontal advection cannot solve the problem of the Yagur anomaly.

b. *Wind-channeling hypothesis*

The 1992/93 wind observations suggest that wind channeling is strongly associated with the Yagur enhancement, since positive enhancements occurred only when the winds on the opposite sides of the mountain were horizontally converging, while negative enhancement occurred when airflow was uniform throughout the region. We found, on enhancement days, that southwesterly flow by the western side of the Carmel was accompanied by southeasterly flow on the eastern side of the Carmel. Similarly, westerly flow on the western side of the mountain was accompanied by northwesterly flow on the eastern side. We suggest, therefore, that the Carmel ridge and Alonim–Shfaram hills cause channeling of airflow parallel to the mountain. When the general (synoptic) flow in the area is westerly, ground winds are deflected by the northern edge of the ridge and become northwestern at the lee side of the mountain in the area of Yagur (Fig. 6b). When the

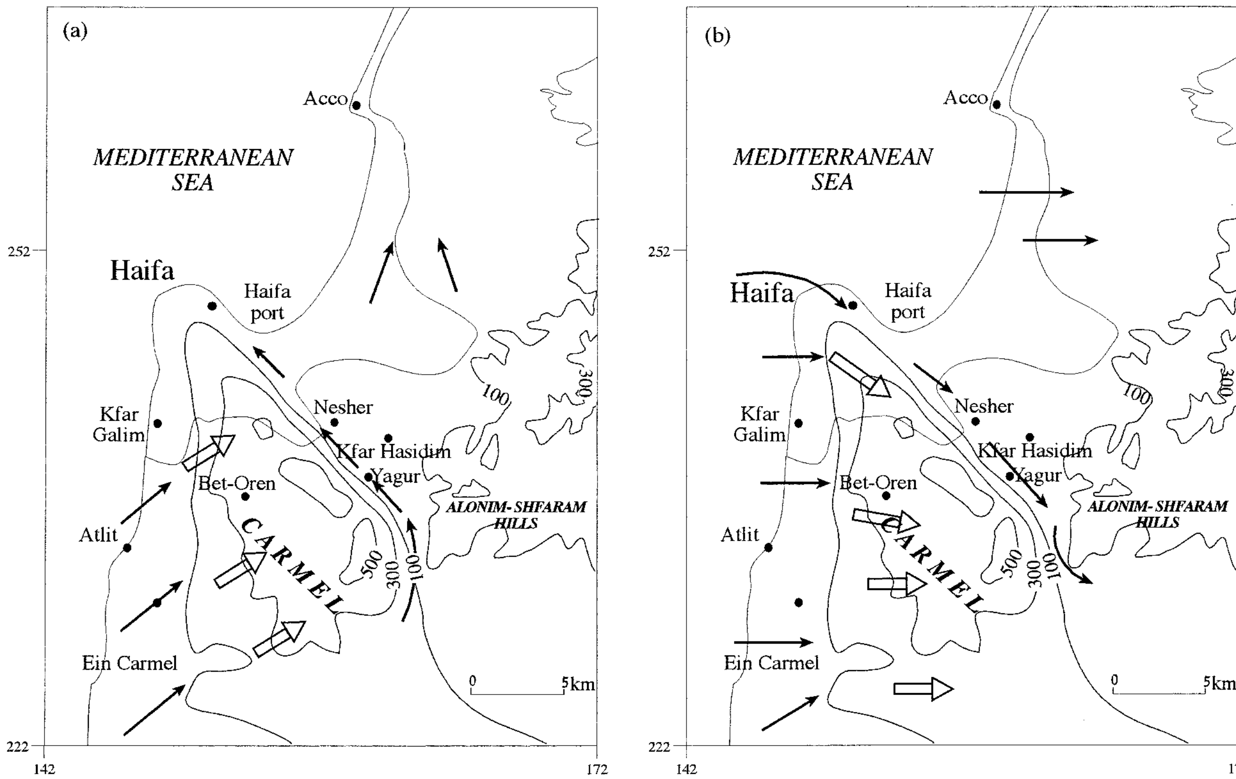


FIG. 6. Schematic directions of ground and gradient wind (upper air based on the radiosonde data of Bet-Dagan near Tel Aviv) on ''enhancement days'' (a) with southwesterly wind field, (b) with northwesterly wind field.

general flow in the area is southwesterly, the ground winds are channeled by the narrow passage between Mount Carmel and the Alonim–Shfaram hills and become southeasterly in the area of Yagur (Fig. 6a). In both cases, divergence of the upwind flow is followed by horizontal convergence at the lee of the mountain. We therefore suggest that the process of convergence at the lee of the Carmel is the dominant cause of the Yagur anomaly. Our explanation of flow channeling parallel to the ridge is supported by the wind roses of the Haifa-port and Yagur stations (Fig. 5), both located at the lee of the Carmel, that present wind directions parallel to the ridge axis.

The flow pattern found here fits the aforementioned flow-channeling hypothesis. However, in contrast to our original hypothesis, we found that the flow pattern can occur both under the conditions of general northwestern flow and under conditions of general southwestern flow.

Further support to the horizontal convergence due to channeling is found in Alpert et al. (1988), where one-level modeling for diagnosing surface winds over the complex terrain in the northern part of Israel during rain was performed. The case is of a Cyprus low on 30 January 1985, with southwesterly flow over the Carmel (Fig. 1 in Alpert et al. 1988) accompanied by rainfall. The model that simulated surface winds clearly shows a strong convergence line along the lee of the Carmel passing over Yagur (Fig. 7a). It should be stressed that the wind field model was illustrated in several studies as capable of simulating flow over complex terrain and does include nonlinear physics of the boundary layer such as nonlinear advection, friction, Coriolis force, and diabatic heating (Alpert 1988).

c. Sharon's hypothesis

As mentioned in the introduction, Sharon (Sharon and Arazi 1993) tried to explain similar rain anomalies using the ''eddy hypothesis.'' Using a numerical model, he simulated a pattern of flow that might develop along a schematic ridge the size of the Carmel (Fig. 7b). Sharon's model predicts opposite surface ground wind directions on either side of the ridge. Our flow pattern (Fig. 6) on the other hand, shows perpendicular wind directions on both sides of the ridge. Since Sharon's wind analysis is a two-dimensional vertical cross section, and ours is a two-dimensional horizontal one (Figure 6), it seems that the findings of the two studies do not, necessarily, contradict each other. Moreover, it is possible that they are two different views of the same phenomenon. Some further surface and upper-level wind observations are needed to resolve this debate.

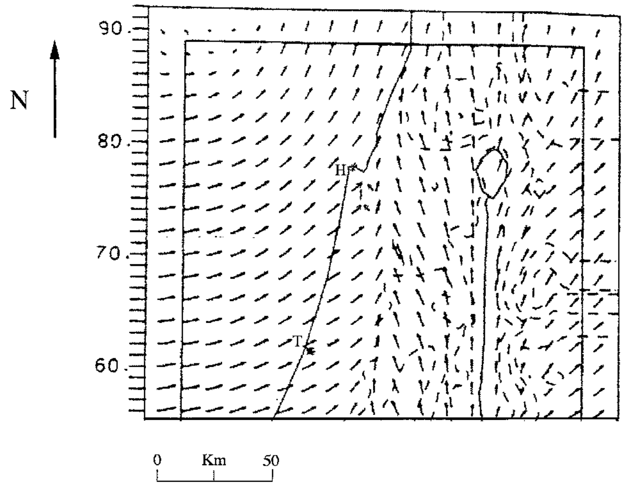
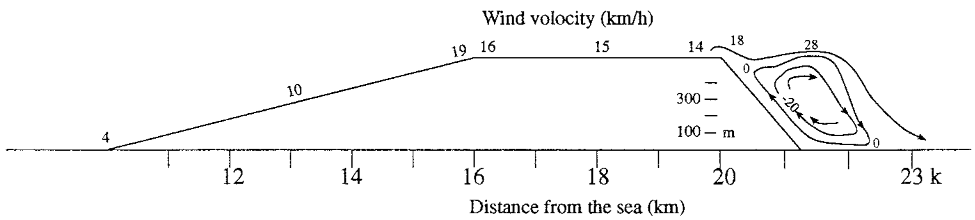


FIG. 7. (a) Model-simulated surface winds for 1500 UTC 30 January 1985. Scale for wind velocity (m s^{-1}) is on the lower left side. Letters in the figure represent the location of the cities: H—Haifa; T—Tel Aviv (after Alpert et al. 1988). (b) Sharon's vertical cross section lee eddy suggestion: a CSU/RAMS model simulation of a flow along a schematic ridge of the Carmel size. The distance (km) from the sea and the wind speeds (km h^{-1}) are marked below and above the topography, respectively. Input wind speed is 15 km h^{-1} at the sea coast (after D. Sharon 1994, personal communication).



6. Some case studies

Three rain spells, taken from the 1992/93 rain season, were chosen and the following fields were analyzed: the synoptic state, wind directions, precipitation amounts, and the rain enhancements measured at Yagur. Figures 8–13 are wind direction maps corresponding to 0100 and 1300 LST. The determination of the wind directions considered general wind directions at times before and after the corresponding time.

a. Rain event of 7–11 January 1993

A Cyprus low that formed over the northeastern Mediterranean sea and southern Turkey caused stormy weather over Israel, giving rise to the passage of a cold front over Israel and resulting in much rainfall in the study area (an average cumulative amount of 90–100 mm of rain during the episode). During the first four days (Fig. 8a), rain was greatly enhanced in Yagur, as compared to the Carmel upwind coast. On the last day, however, there was negative enhancement. Examination of wind directions showed that on positive enhancement days the wind indeed blew in the enhancement pattern described in section 5b, that is, southwesterly winds on the Carmel coast (upwind) gave rise to southeastern flow on the lee side of the mountain (Fig. 8a), while westerly winds on the western slopes gave rise to northwesterly flow on the lee side (Fig. 8b).

On the other hand, on the last day of this rain spell (11 January 1993), the day of negative enhancement, the wind directions were nearly uniform throughout the region, at times northwesterly (Fig. 9a), at others southeasterly (Fig. 9b). These uniform directions cannot lead to a channeling of the flow, and probably that is the reason for the negative enhancement. It should be stressed that the uniform direction is the case where convergence cannot be generated.

Note that Fig. 9a indicates a situation where in principle there could be an advection effect because the wind blows from the northwest and must climb the mountain on its way to Yagur. Nevertheless, there was no positive enhancement at Yagur. This supports our suggestion that advection alone cannot explain the leeside rainfall enhancement.

b. The rain spell of 31 January–3 February 1993

This rain spell, as well, was caused by the effect of a Cyprus low. Large amounts of precipitation over the study area (an average cumulative amount of 50–60 mm) were associated with the accompanying cold front. On the first day of this event, Yagur received an impressive 250% enhancement of rain compared to the coastal region and a 41% enhancement on the second day. The enhancement was negative, however, on the last two days.

Figures 10a and 10b depict the wind directions during the first 24-h rain period and one can clearly see the proposed reason for the impressive enhancement. Most of the day, the winds blew in an enhancement pattern: a south-southwesterly wind on the Carmel coast gave rise to a southeasterly wind on the lee side of the moun-

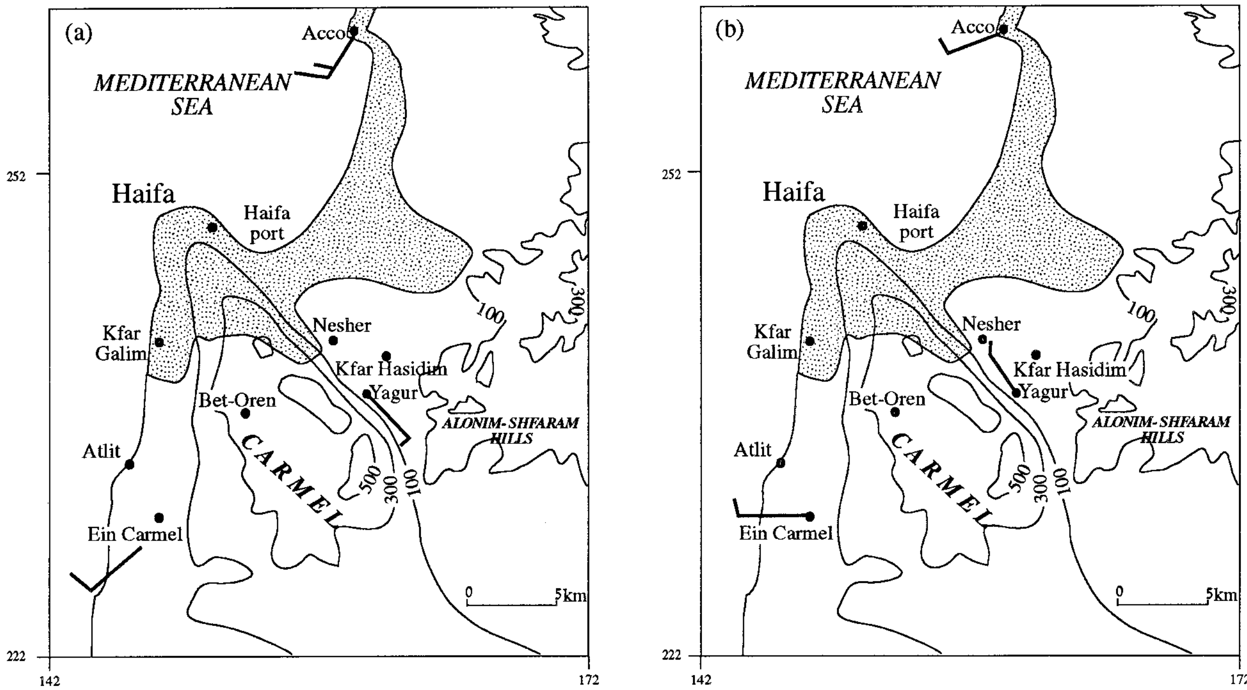


FIG. 8. Ground wind speed and direction on 8 January 1993. Rain at Yagur (0800–0800 LST)—24.0 mm and at Carmel coast—12.6 mm; (a) around 1300 LST, (b) 0100 LST on the next day.

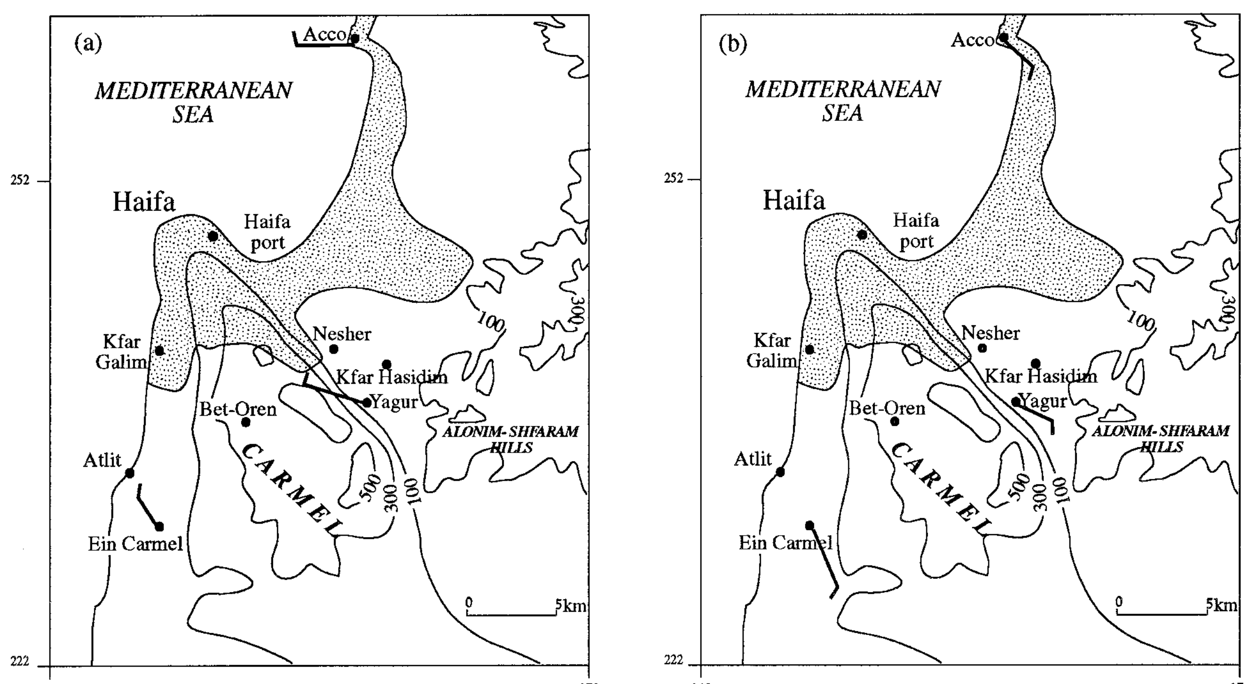


FIG. 9. Ground wind speed and direction on 11 January 1993. Rain at Yagur (0800–0800 LST)—2.0 mm and at Carmel coast—6.1 mm; (a) around 1300 LST, (b) 0100 LST on the next day.

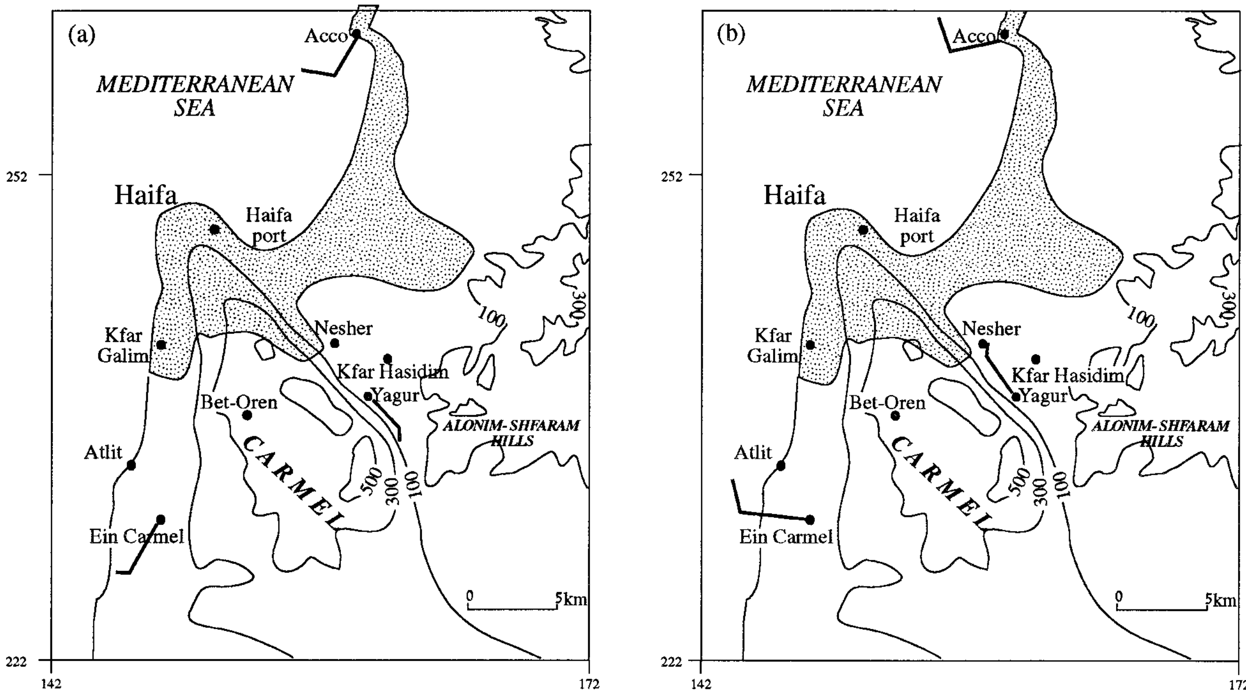


FIG. 10. Ground wind speed and direction on 31 January 1993. Rain at Yagur (0800–0800 LST)—31.5 mm and at Carmel coast—9.0 mm; (a) around 1300 LST, (b) 0100 LST on the next day.

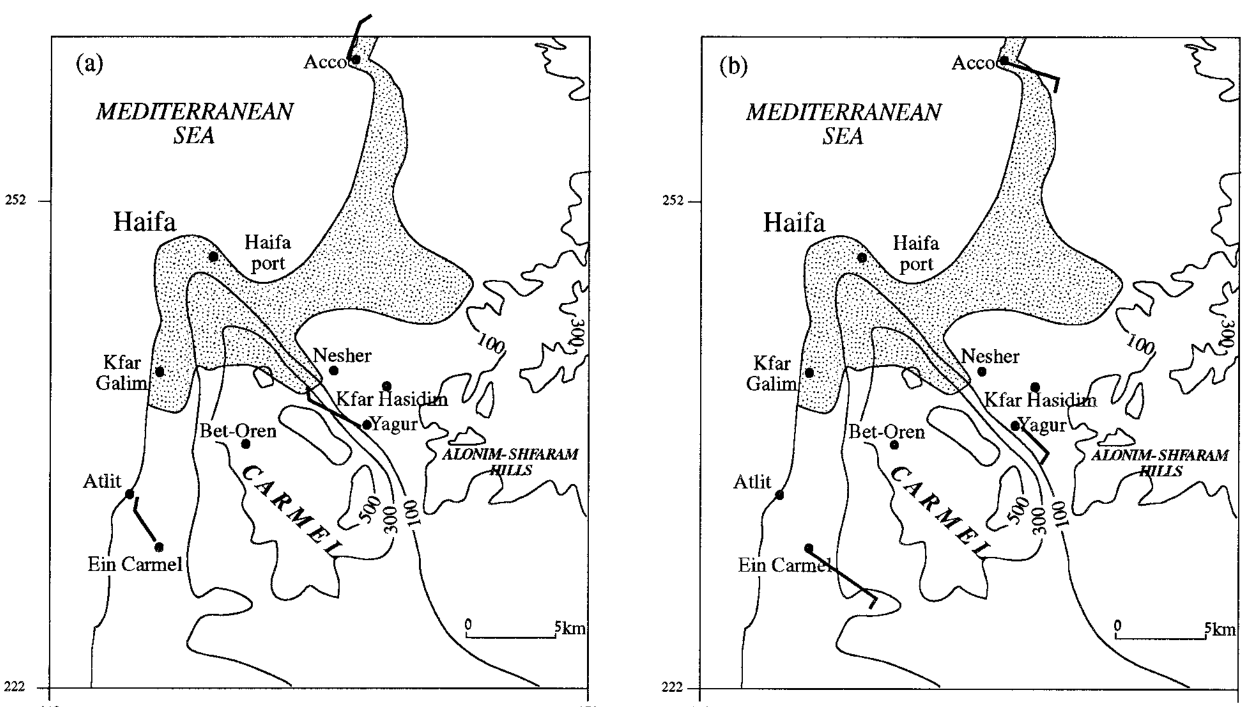


FIG. 11. Ground wind speed and direction on 2 February 1993. Rain at Yagur (0800–0800 LST)—8.1 mm and at Carmel coast—15.0 mm; (a) around 1300 LST, (b) 0100 LST on the next day.

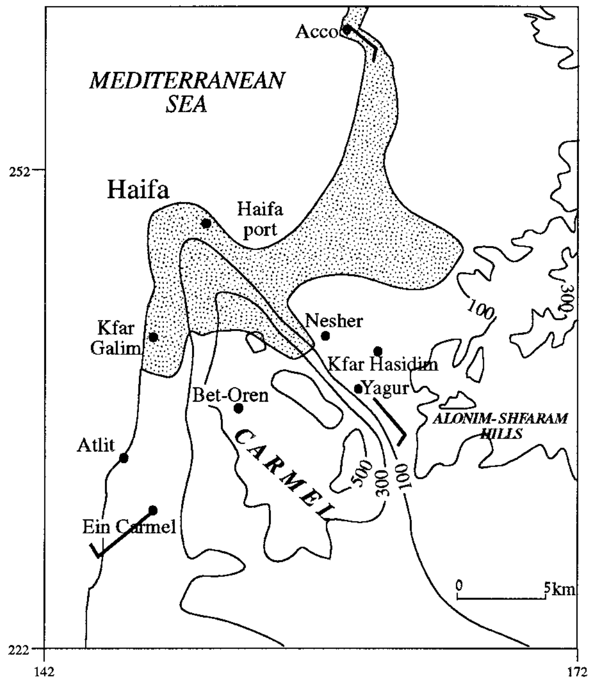


FIG. 12. Ground wind speed and direction on 8 February 1993. Rain at Yagur (0800–0800 LST)—35.0 mm and at Carmel coast—17.5 mm, around 1300 LST.

tain, and a westerly wind on the coast gave rise to a northwesterly wind on the lee side.

On that first day, the Haifa-port rain gauge also received greater quantities of rain than the Carmel coastal region—more than twice as much. Since such wind directions put Haifa-port also in the lee side of the Carmel, it seems probable, therefore, that the same mechanism suggested for explaining the Yagur anomaly can explain the enhancement at Haifa-port.

Figures 11a and 11b depict the circulation on the 2 February 1993, a day of negative enhancement. Winds blew from similar directions throughout the region, not conductive to horizontal convergence. During the last day in this spell, which was the second negative enhancement day (3 February 1993; −53%), the flow pattern was similar to that of the previous day.

c. *Rain event of 8–13 February 1993*

This event, too, was caused by a Cyprus low with a cold front, resulting in large amounts of precipitation (an average cumulative amount of 60–80 mm). The main enhancement during this event occurred on the first day (+100%). Analyses indicated that for most of the day the flow pattern was the typical one for enhancement (Fig. 12). Here, too, on the first day, Haifa-port received quantities of rain similar to that of Yagur, in fact more than twice as much as the Carmel upwind coast. Interestingly, the cumulative rain in Haifa-port for the entire event was even greater than in Yagur. As mentioned before, it seems that Haifa-port can also enjoy rain enhancement, at times, even more than Yagur,

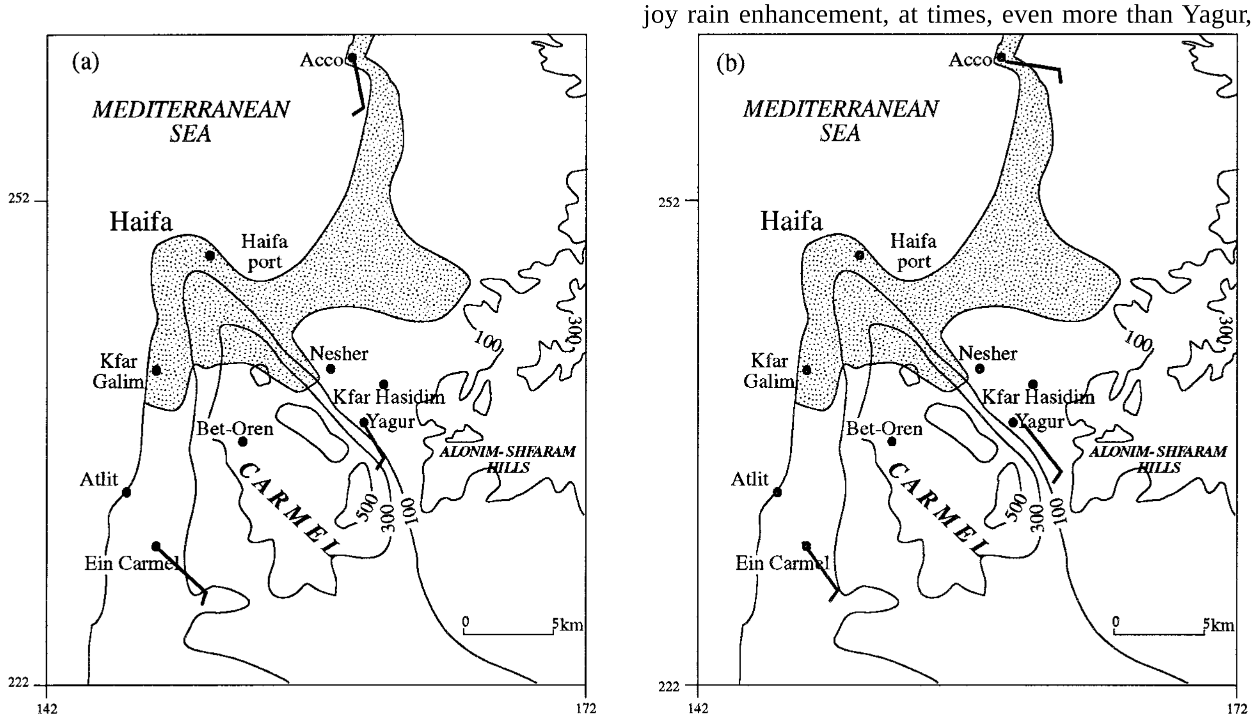


FIG. 13. Ground wind speed direction on 9 February 1993. Rain at Yagur (0800–0800 LST)—4.7 mm and at Carmel coast—6.0 mm; (a) around 1300 LST, (b) 0100 on the next day.

although the average annual rainfall at Haifa-port is much less than at Yagur and similar to that of the Carmel coast. On the second day of rain, there was negative enhancement (−21%), and indeed, as indicated in Figs. 13a and 13b, wind directions exhibited a negative enhancement pattern.

7. Conclusions

This study examined and tested different hypotheses explaining the rainfall enhancement anomaly of Yagur. Results of the study indicated the existence of a flow pattern at the lee of the mountain, which caused local rain enhancement in the area of Yagur. We conclude that the flow past Mount Carmel caused divergence of the winds over the western (upwind) side of the mountain and horizontal convergence over the eastern (lee) side. This flow pattern, which was also revealed on a one-level model of wind field over a complex terrain, is similar to the suggested ''flow-channeling'' hypothesis. However, in contrast to the original hypothesis, observations have shown that this flow pattern can exist both with northwesterly and southwesterly gradient winds and in fact during most rain events in the area. Confirmation of Sharon's hypothesis and the lee wave (with a reversal branch flow on the upstream on the lee side) hypothesis needs 3D simulations.

In the present study, we used an orographic model to simulate the precipitation patterns over and to the lee of Mount Carmel. The model accounts primarily for the local geometric uplifting by the topography. Since it includes simulation of the advection, it can represent the cloud or precipitation advected over the ridge. Eddies or other complex flows that may be formed by the mountains are not considered in this 2D advection model. The large discrepancy between model and observations in the lee of the mountain could perhaps be overcome by applying a 3D model that can handle lee eddies and channeling phenomena on various scales. Yet a theoretical model does not stand by itself. Well-established sets of empirical meteorological observations are required to define initial and boundary conditions of the model, to scale their parameters, and to verify simulations. The realistic simulation of the circulation and precipitation complex in and around the Carmel range that will provide a rigorous test of the hypotheses suggested in this paper awaits additional observation of surface and upper-air wind observations.

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