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Reassessment of rain enhancement experiments and operations in Israel including synoptic considerations

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ABSTRACT

A re-analysis of the results from cloud seeding in northern Israel is described. The analysis covers the period of the randomized Israel II experiment (1969–1975) and the subsequent period (1975 to the present) where operational seeding is being conducted. The evaluation is carried out using the double ratio method, as was done in the past. We analyzed the precipitation data in the north of Israel before and during the seeding period, stratified the data based on synoptic conditions and compared the results with an area to the south that had been unseeded during the seeded days in the north. The results show that during Israel II the rain enhancement in the target area in the north of Israel was about 12%, similar to the results reported previously. However, these results have two major problems: 1) During Israel II the rainfall ratio between the inland areas (target) and the coast (control) was unusually higher in comparison with the unseeded periods prior to the initiation of the experiment and also, in comparison with the seeded period following Israel II. 2) Comparison of the double ratio in the north during the Israel II experiment was found to be slightly lower than that in an equivalent unseeded area to the south on the same days (1.15 vs. 1.13). This implies that the high double ratio values in the north may not be a consequence of successful cloud seeding but of preferred synoptic conditions during seeding in which inland rainfall is relatively higher, i.e. deep cyclones over the E. Mediterranean.

The analysis also shows that during Israel II the frequency of deep lows that accompanied the rainy days was higher on seeded days than during unseeded ones with stronger westerly winds. This can explain why on seeded days, rain clouds penetrated more efficiently towards inland areas resulting in higher rainfall ratios of target (inland mountainous)/control (coastal strip) on seeded days both inside and outside the seeding project area. Furthermore, the double ratio obtained for the whole study period (1.00) also strengthens the point that the high double ratio value during Israel II experiment is not the result of cloud seeding.

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1. Introduction

Deliberate cloud seeding for rain enhancement by injecting efficient ice nuclei into clouds, has been practiced since the mid-20th century. These efforts have improved our understanding about the processes that lead to cloud and

precipitation formation and the effects of seeding aerosols on them. Unfortunately, only a few large comprehensive projects have been conducted in which both physical and statistical evaluations were reported. It is clear that definite proof of rain enhancement from cloud seeding projects would demonstrate that precipitation is at least partly connected to the type of aerosols that are injected into the clouds. It would also shed light on one of the poorly understood links in the long chain of processes leading from cloud initiation to precipitation on the ground. More comprehensive assessments of the current status of cloud seeding research can be found in:

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National Research Council (2003), Cotton and Pielke (2007), Silverman (2001, 2003), Garstang et al. (2005), WMO statements of weather modification (2001, 2007) and Levin and Cotton (2008).

In Israel, three cloud seeding experiments were conducted since the early 1960s and an extended program of operational seeding has been going on in the North since 1975. The Israeli experiments, called Israel I and Israel II were conducted mostly by airborne seeding along prescribed seeding lines (Fig. 1 presents the seeding lines, the target and control areas of these experiments and the operational period). These experiments were considered examples of success, because early reports showed that the rain clouds over Israel are mostly cold winter continental cumuliform clouds, associated mostly with cold fronts and post-frontal bands in which rain forms mostly through the growth of ice crystals (e.g. Gagin, 1975; Gagin and Neumann, 1981). It was also argued these clouds are susceptible to seeding because they contain

insufficient ice crystals and have high concentrations of small cloud drops which inhibit the development of rain by the warm rain process, i.e., growth by coalescence. The hypothesis, therefore, was that seeding these clouds with silver iodide particles, efficient ice nuclei, would increase ice crystal number concentrations leading to rapid development of precipitation through the Bergeron-Findeisen and riming mechanisms. This hypothesis was supplemented with statistical results of the two randomized experiments showing enhancement in annual rainfall of between 12 and 15 % in the Galilee area in the north of Israel (Gagin and Neumann, 1981; Gabriel and Rosenfeld, 1990). Statistical results of the southern areas in Israel II showed no increase in rainfall with a hint of a negative effect but not statistically significant (Gabriel and Rosenfeld, 1990; Rosenfeld and Farbstein, 1992). Following the apparent success of the two experiments it was decided to start the operational seeding in the north, a process that has been ongoing since 1975.

In the mid 1990s a number of questions were raised regarding the success of the Israeli experiments. Levin et al. (1996) showed that the clouds in Israel often have ice crystal concentrations greater than 100 L^{-1} at temperatures as high as -10°C . These observed concentrations are more than an order of magnitude higher than was reported by Gagin (1975) for the clouds in this region. In addition, the cloud droplet number concentrations were often $300\text{--}450 \text{ cm}^{-3}$, much lower than previously reported, making them somewhat intermediate between continental and maritime.

Nirel and Rosenfeld (1995) analyzed the results of the operational cloud seeding that have been going on since 1975 and concluded that enhancement of only about 6% has been achieved in the Galilee Mountains during this period. Rangno and Hobbs (1995) re-analyzed the data from Israel II and concluded that the experiment could have suffered from type 1 statistical error in which the null hypothesis is wrongly rejected. They showed that during Israel II similar increases in precipitation occurred in Lebanon and Syria to the north in regions where no seeding took place. This paper generated much discussion in the literature (Rosenfeld, 1997; Ben-Zvi, 1997; Woodley, 1997; Dennis and Orville, 1997; Rangno and Hobbs, 1997), and raised new questions about the success of what was considered to be a success story of rain enhancement (Mason, 1982; Kerr, 1982).

In the early 2000s at the request of the Israeli Hydrological Service, Kessler et al. (2006) in a comprehensive report (in Hebrew) analyzed the effects of seeding in Israel. Two methods of analysis were used; the double ratio and the regression methods. Although in the second method some positive enhancement was found, Kessler et al.'s main conclusion was that the operational seeding does not contribute to the total rain amounts on the ground. They further argue that positive seeding effects occurred on days with less than 5 mm/day. Negative effect is observed when seeding is done on days with more than 15 mm/day thus the net effect is that there is no significant enhancement in rainfall due to seeding (Sharon et al., 2008).

Givati and Rosenfeld (2005) and Rosenfeld (in private communication on page 33 in Kessler et al.) raised two possibilities to explain the results of Kessler et al. (2006). The first one is that there is a constant decrease with time in the

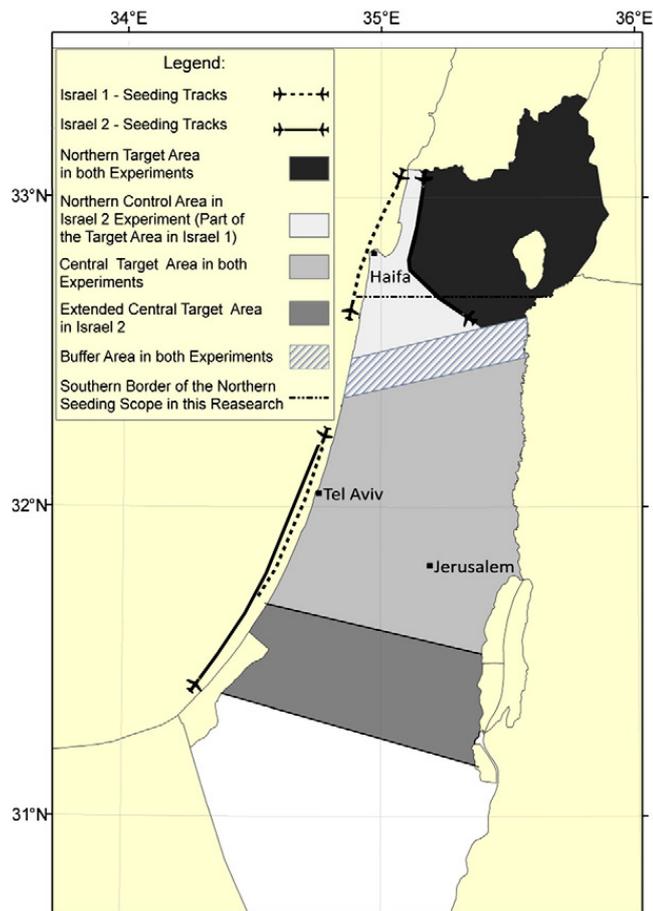


Fig. 1. A schematic map of the seeding lines used during Israel I, II, and the operational periods. Also shown are the areas used as target and control during Israel II and the operational periods and the buffer used during Israel I and II. Note that the southern seeding line in Israel II was extended southward as compared to Israel I. The dashed and dotted line is the southern boundary of the target area for which mean daily rainfall for seeded and unseeded days was calculated. Note that the DR calculations were carried out a little north of the southern boundary some of the stations in the omitted area are not located downwind (250° azimuth) of the control stations.

ratio between the target and the control areas because of enhanced pollution in the control area, suppressing the orographic rainfall in the target area located downwind (see Fig. 1). According to Givati and Rosenfeld (2005), the seeding operations moderated this suppression. Therefore, they argued, the target/control ratio during historical unseeded days during which time pollution was low, cannot be compared to current seeded days. The second explanation is that most of the unseeded days that were chosen by Kessler et al. during the operational stage of the project were in the last part of the rainy season when meteorological and synoptic conditions are naturally in favor of heavier rain in the mountainous (target) area. Thus, they concluded that the results of Kessler et al. do not correctly represent annual rainfall ratios.

Alpert et al. (2008) and Halfon et al. (2009) challenged the first explanation by Givati and Rosenfeld because they did not find any decrease in time in the precipitation ratio between the mountains=target and the shore=control that could be attributed to pollution effects, especially at the mountains upslope where the sharpest decrease in precipitation was expected to take place. Alpert et al. (2008) showed that the decrease in the rainfall ratio was contributed by rainfall increases in the seashore inland stations, probably associated with urban rainfall increases. When upwind coastal stations were chosen no decrease in rainfall ratio was found.

The aim of the present paper is to help resolve these conflicting statistical results and to base the analysis on a larger data base and a different methodology including analysis of data up to 2007. For this purpose we make use of the largest data base used so far for evaluating the seeding projects both in terms of number of stations and in the extent of the analyzed period. This is done by analyzing the precipitation data in Israel before and during the seeding period, by stratifying the data, for the first time, based on synoptic conditions and comparing the results with an unseeded adjacent area to the south. For this purpose the present analysis covers the Full Period from 1949 to 2007 during which time the two experiments Israel I and Israel II (from 1961 to 1967 and 1969 to 1975, respectively) and a lengthy operational period (1975–present) were conducted. There was a third experiment Israel III that targeted the southern region, which is outside the region of interest of this paper. For the purpose of clarity the Full Period 1949 to 2007 will be referred to as the “Full Period” and the period of Israel II experiment (1969 to 1975), which was carried out based on the same methodology of the operational period will be called “Israel II” The seeded rainy days during Israel I were filtered out in this analysis because the seeding line used in this experiment was farther west from that used in Israel II (see Fig. 1), thus eliminating the control area near the coast that is necessary for the analysis.

2. Data base

The data base consisted of the following items:

- a) Official data from “Electrical and Mechanical Services” (EMS), the company responsible for the seeding. These consisted of data from seeded and unseeded days during Israel II and during the operational period. The

area covered by this data included the northern coast and the inland stations in the Galilee and the Hula Valley to the east of it (see Figs. 1 and 3).

- b) The Full Period contained daily rainfall amounts from 1949/50 to 2006/07 in 140 long record rain gages of the Israeli meteorological service (IMS) in the north of Israel (lat 32.75–33.30). In addition, IMS data from 106 rain gage stations in the middle of the country for the period of Israel II (1969–1975). This data is used for comparison of inland/coastal rainfall ratios between the center and the north of the country.
- c) Daily Synoptic type conditions in the Eastern Mediterranean using the semi-objective classification of Alpert et al. (2004). This classification is based on the daily sea level pressure maps for 12 UTC, based on the NCEP/NCAR dataset, 2.5° × 2.5° resolution (Kalnay et al., 1996; Kistler et al., 2001).
- d) Radio-sonde archive data from the IMS in Bet Dagan for the period (1957–2007).

3. Method of analysis and procedure

- a. Investigation of the success of cloud seeding for the Full Period and for “Israel II” experimental period
This investigation was carried out in the same way as it had been done in the past (e.g. Gagin and Neumann, 1981), namely, by the method of Double Ratio, DR. This ratio is defined as:

$$DR = (Ns / Cs) / (Nu / Cu) = (Ns / Nu)(Cu / Cs) \quad (1)$$

Where N and C are the daily rainfall in the target and the control stations, respectively and s and u refer to seeded and unseeded days, respectively.

In contrast to the way the analysis was done in the past (Gagin and Neumann, 1981; Gabriel and Rosenfeld, 1990; Nirel and Rosenfeld, 1995) in which the north area was used as a single unit or it was divided into a number of sub-units, in this paper we map the spatial distribution of DR by taking the values of the individual stations and interpolating them in order to create a continuous map. The average value of these maps was compared with the average DR value of the stations without interpolation and was found to deviate by less than 1%. The advantage of the mapping method is that it allows a better look at the spatial distribution and the geographic variations of the DR values. The following steps were required in order to perform the mapping:

- i) The definition of seeded and unseeded days
For the operational period, only days that were actually seeded by airplane were classified as such and unseeded days were those days when airborne seeding was not carried out. Unseeded days were those days that fell during the pre-seeding period or days in which seeding from airplanes was not conducted due to some operational problems or due to inappropriate conditions for seeding. In reconstructing Israel II we used the classification described above for seeded and unseeded days. We then compared the results with those based on the original guidelines set by the designers of the

experiments, namely, seeded days are all the days that were designated for seeding (even if in reality they were not seeded) and unseeded days were those that were not designated for seeding.

Since many rainy days were sporadic and local, it was problematic to compute the DR between the target and control areas. In fact, because days with light rain were often not seeded, the number of unseeded days far exceeded those that were seeded. For the analysis we preferred to obtain similar numbers of seeded and unseeded days as well as days with similar spatial distribution. Fig. 2 shows that the difference between the number of seeded and unseeded days decreases with the increase in the percentage of area coverage by the rainfall. We decided to compute the ratio only for those days in which rain was recorded in at least 75% of the active stations. This is because even if we include all the rainy days, including those that are very local, the total accumulated rainfall would increase to only 1% in the seeded days and to 10% in the unseeded days. In addition, in our analysis we included only unseeded days from the seeding season (November to April) in order to avoid using days that are possibly affected by different synoptic and meteorological conditions.

The total number of unseeded days in which rain was recorded in at least one station was 6122. The total number of days that complied with the criterion above (rain recorded in at least 75% of the stations) dropped to 1301 days. In contrast, seeding was conducted on almost all the days in which rain was widespread (1398 days); therefore, applying the above criterion reduced the number of rainy days in the data only from 1398 to 1088.

- ii) The choice of rain gage stations for computing the DR Stations in the north of Israel were chosen where the standard error² of the daily rainfall amount did not exceed 8% from the daily average. This value was chosen in order to obtain robust results, taking into account the high standard deviation of the daily rainfall in the study area. In fact, the mean amount of daily rainfall was about 10 to 15 mm and the standard error of the daily amount was often of a similar magnitude. It was, therefore, necessary to accumulate more than 150 days in each category of seeded and unseeded days in order to abide by the rule above. There were 35 stations located in the control area, west of the seeding line that fit the above criterion and 106 stations located east of the seeding line and thus fall into the target area. Since the numbers of seeded and unseeded days during Israel II were not large, we relaxed the criterion and included in the analysis the stations in which the daily standard error did not exceed 12% of the daily average. Out of the 141 stations operated during Israel II, 108 complied with the above

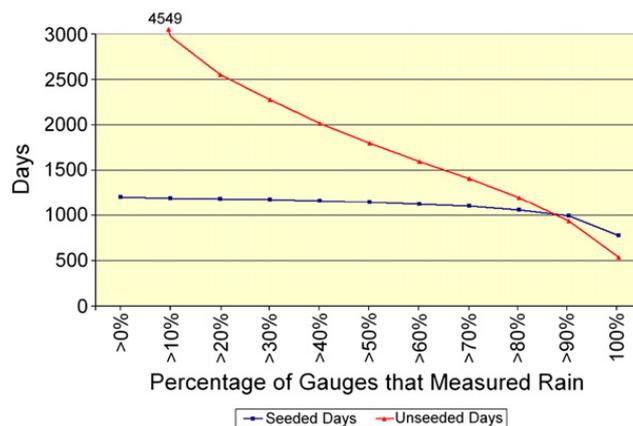


Fig. 2. The number of seeded and unseeded days and the corresponding percentage of the operated gauges that recorded rain.

relaxed criterion, out of which 32 were in the control area and 76 in the target area.

- iii) Computing average rainfall on seeded and unseeded days

Only two stations had a complete record for the Full Period. Most had partial data because they started their measurements after the initial research period or terminated before the end of the period. This necessitated making some adjustments in order to obtain a proper daily rainfall amount. The method we used is described in Appendix A and also in Halfon et al. (2009).

- iv) Mapping the average daily amounts of seeded and unseeded days

After having adjusted rainfall amounts for seeded and unseeded days in each of the stations for the whole study period, it was then possible to map the daily amounts of seeded and unseeded days (see details about the interpolation method in the caption of Fig. 3).

- v) Mapping the DR

The DR mapping was carried out by dividing the daily average maps of the seeded/unseeded days in the target area and then dividing this map by the corresponding ratio in the control area (see Section A.2 in the Appendix A).

Comparison of the mean DR values of the interpolated maps with the mean DR values measured only in the stations (without any interpolations) showed differences of less than 1%.

- vi) Cropping the target area from the DR maps

The target area was defined as follows: the north boundary was the Lebanese border and on the east, the Syrian border. Maps relating to Israel II do not include the Golan Heights since there was only one rain gage station in this region that worked throughout the experimental period. On the west, the area was bounded by the seeding line (Gagin and Neumann, 1981). In the south, the boundary was along an azimuth of 250° in the NE direction from the southern end of the control area (see Fig. 3C,F,I). This southern boundary was chosen because the average wind direction during rainy periods is 240–250° and thus areas south of this line are not downwind of the control area.

² Standard error is defined as

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}}$$

where s is the standard deviation of the daily rainfall in the station in mm, n is the number of rainy days measured in the station.

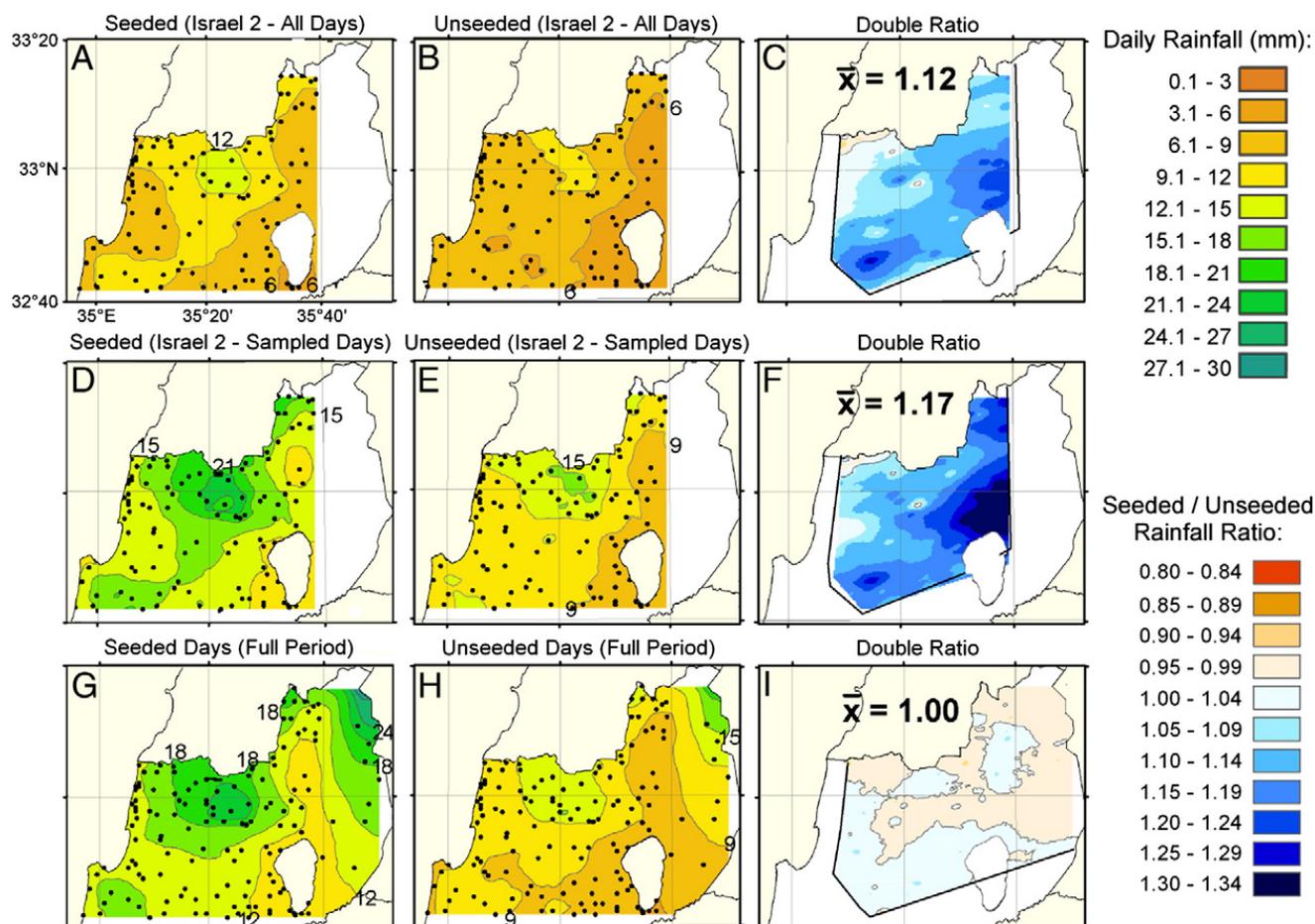


Fig. 3. The average daily rainfall on seeded (A, D, G) and unseeded (B, E, H) days. The right column (C, F, I) shows the mapping of DR. The differences between the results of Israel II (panels A, B, C for all allocated days and panels D, E and F for the sampled days, after applying the methodology described in Section 3a) and the Full Period (panels G, H, I), are shown. Mapping of the daily amounts was performed using the method called Inverse Distance Weighted (IDW) with the software ARcMap 9.3. The interpolation was done by using the ratio of the average daily amounts to the annual amount as follows:

- In order to smooth out the strong variations due to topography, we used the ratio of the average daily to the average annual rainfall amounts, since the variations in the latter are not as large.
- The above ratios were mapped using the IDW method. The definition of the leading exponent that leads to the minimal error of this function was performed using the program Geostatistical Analyst.
- The daily seeded and unseeded maps were obtained by multiplying the value in each grid space (obtained above) by the annual average map for period 1961–1990.

b. Examining the ratio between sub-areas in the target/control during time segments in the Full Period

Rainfall from convective clouds is often local and highly variable. Often rainfall is recorded in one station and not in another one located nearby. This variability can be partly overcome in the analysis if a group of stations are lumped together into a cluster that is chosen based on clear geographical and climatological criteria. In order to examine the seeding efficiency above different geographic conditions involving different amounts of orographic rainfall, the mountainous seeding target zone was divided into three sub-areas. The examination was based on the ratio of the average daily rainfall in three clusters of stations in the sub-areas to the average value of a cluster in the control area (see Fig. 4).

i) The choice of the clusters

The three clusters were chosen based on topographical criteria and it is similar to that used in the original

analysis of [Gagin and Neumann \(1981\)](#). One cluster is on the western side of the water shed, similar to sub-area n1 in [Gagin and Neumann \(1981\)](#) and the second cluster is on the eastern side of the water shed, n3 in the above reference. The third cluster represents the Hula valley, n6 in the original clustering. The three sub-areas are located downwind of each other (azimuth of 245°) and represent the heart of the target area of Israel II, namely, the upper Galilee and the Hula Valley. All the control stations except for the ones at the far north and south ends of this area, which are not directly upwind of the clusters, are included in the analysis (Fig. 4A).

ii) Computing the daily spatial mean in each cluster

Since not all the stations were operational on the experimental days, it was necessary to adjust the average in each cluster based on the method described in [Appendix A](#). This was done as long as at least one half of the cluster stations operated on that day. The

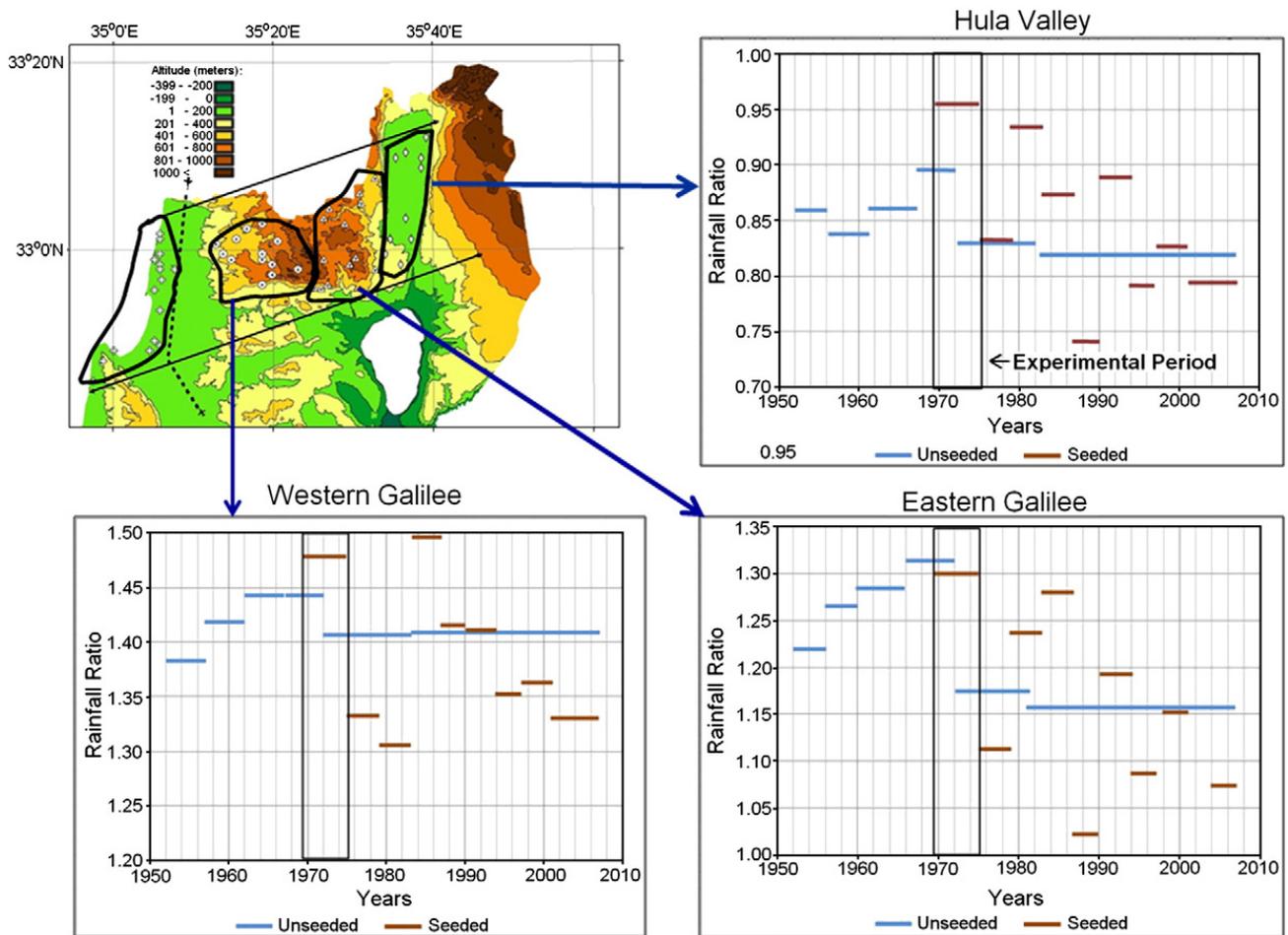


Fig. 4. Target/control ratio on seeded and unseeded days using equal segments of accumulated rainfall. (A) Location of the four clusters. (B, C, D) Rainfall ratios between the 3 target clusters, indicated by arrows and the control cluster. The rectangles indicate the Israel II experimental period. Note that from 1960 to 1967, Israel I seeding experiment was conducted with seeding lines that are different than those used during Israel II. From these data only unseeded days were considered for this analysis. Also it is important to note that $DR < 1$ corresponds to rainfall ratios on unseeded days (blue lines) that are higher than on seeded days (brown lines).

few cases that did not conform to this rule were deleted from the analysis.

After this filtration process we were left with between 1963 to 2054 days of rainfall in the different clusters.

- iii) Defining the sub-periods for testing the rainfall ratios between target and control clusters

In order to determine the variability of the rainfall ratio between the target and control clusters even after an accumulation of a fair rainfall depth such as the accumulated rainfall for the experimental period, we evaluated the rainfall ratio target/control for a total rainfall amount that is equal to that accumulated during Israel II.

The total accumulated rainfall during the unseeded days in Israel II was 1620 mm. This amount was found to be sufficient to declare the success of Israel II with an increase of 12% in rainfall due to seeding (Gagin and Neumann, 1981). We, therefore, use this amount as a reference for analyzing segments of the Full Period. For this purpose, the rainfall during the Full Period was divided into equal accumulated segments of 1620 mm each. The remaining amount was then equally divided among all the periods. The process was as follows: the accumulated rainfall was first calculated in the control

area for the seeded and unseeded days separately. Once the amount in each group reached 1620 mm, the amount of rainfall in the corresponding days in the target area was accumulated, again separately for the seeded and unseeded days. Then the ratios were calculated. This process was repeated in the control area without overlapping days until 1620 mm were accumulated again, followed by accumulation of rainfall in the corresponding period in the target area.

Fig. 4B–D presents the rainfall ratio between the three clusters and the control. It should be noted that the lengths of the periods are not equal. For example, prior to the beginning of the seeding experiments, it took 3 years to accumulate 1620 mm of rain in the control area during unseeded days. Yet, during the operational period, when the number of unseeded days was limited (most of the rainy days were seeded), the same amount of unseeded rain was accumulated after one to two decades.

- c. Synoptic differences between the seeded and unseeded days during Israel II and the Full Period

Halfon (2008) and Saaroni et al. (2009) found that the depth of the cyclones (lows) and the wind speed at low levels (1000–850 hPa) have the greatest impact on the

rainfall differences between the mountainous (target) area and the coastal (control) area. The strong dependence of the orographic ratio on the wind speed and the functional relationship was discussed by e.g. Alpert and Shafir (1991). The depth of the cyclones (Lows) was used here following Alpert et al. (2004) in which 19 synoptic conditions were defined based on three criteria: the type of system, its location and its depth.

Since most of the rainfall in Israel occurs in the presence of cyclones in the Eastern Mediterranean, and the precipitation ratio between inland and coast is affected by the depth of the systems (Saaroni et al., 2009), we combined the 19 categories into 3, corresponding to that of Saaroni et al. (2009) as follows:

- Deep cyclones; deep cyclones from the east, from the south and from the north of Israel, respectively defined as types 11, 12, 14 in Alpert et al. (2004).
- Shallow cyclones; the remaining four types of cyclones from the above classification (two types of Sharav lows that usually produce very little rain were eliminated).

- No cyclones: the 12 remaining types that were classified as high pressure, troughs and as Sharav lows. Each rainy day in the research area was classified based on the above synoptic criteria. Fig. 5A and B show the distribution of the synoptic conditions during Israel II and during the Full Period, respectively. The examination of the frequency distribution of the different synoptic conditions was based not only on the number of days (Fig. 5A,B 1–2) but also on the total accumulated rain in the study area in each cyclone depth category (Fig. 5A,B 3–4).

d. Dependence on wind speed

The wind speed at 850 hPa was based on the radio-sonde data from Beit Dagan in central Israel. The radio-sonde data for 1957–1964 was for 11 UTC. From 1965 radio-sondes were released at 11 UTC and 23 UTC. The effects of the wind speed of rainfall prior to 1957 were not considered here due to the lack of sufficient upper level data from direct measurements in the vicinity of the research area.

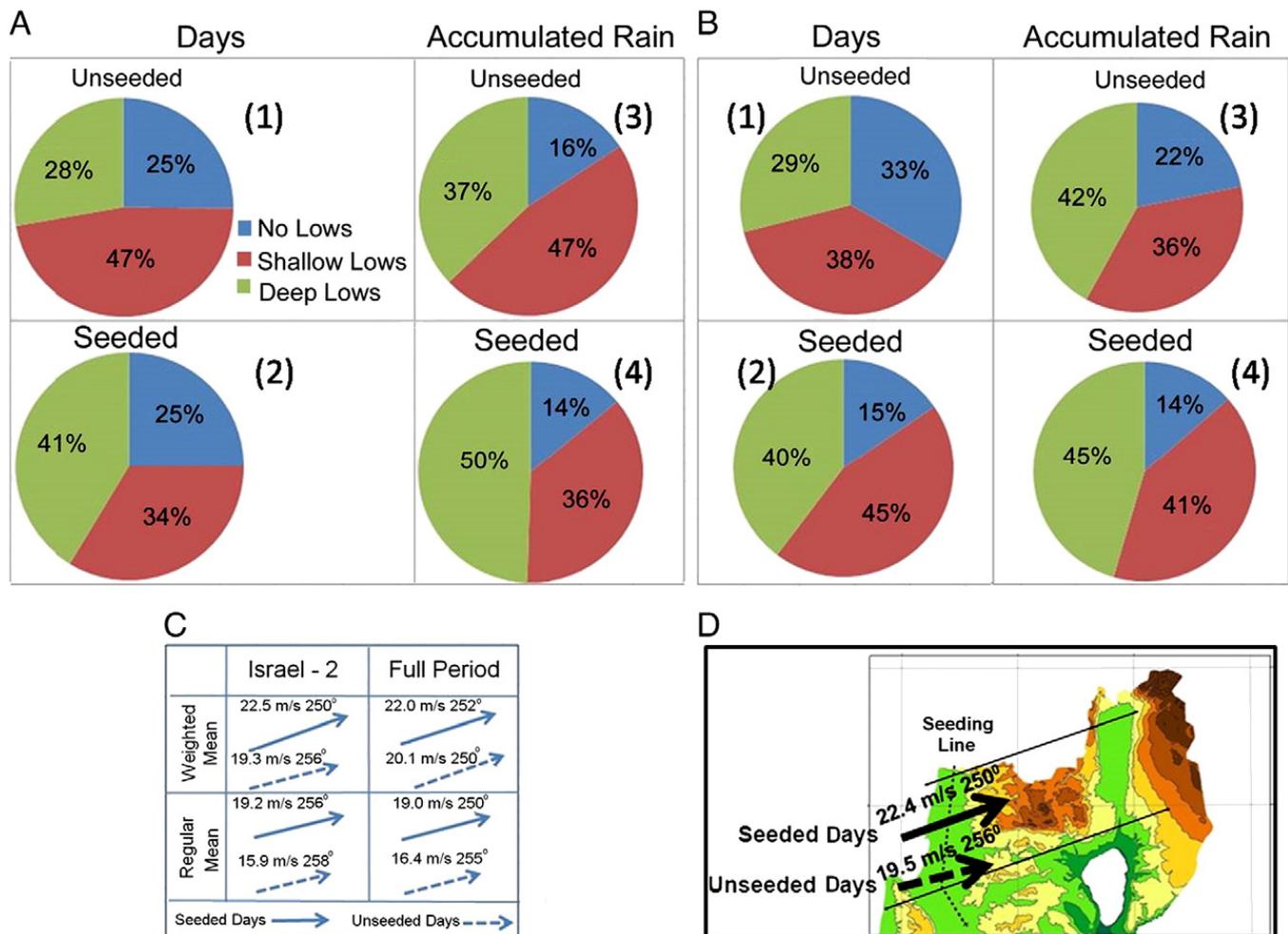


Fig. 5. Differences based on synoptic conditions between seeded and unseeded days: (A) Distribution of the synoptic conditions during “Israel II” experiment: 1–2) based on the total number of the rainy days, 3–4) based on the total accumulated rain in the research area (the method for computing the spatial average of the daily rain in the research area is similar to the method used for the control area, as specified in the Method of analysis and procedure section). (B) As in A but for the full study period (1950–2007). Green indicates deep lows; red indicates shallow lows and blue indicates no lows. (C) Mean wind speed and direction at 850 hPa level as measured by radio-sonde in central Israel during the rainy days of Israel II and the Full Period (see the Method of analysis and procedure section). (D) Mean wind speed and direction projected on the local geography, showing the target and control areas.

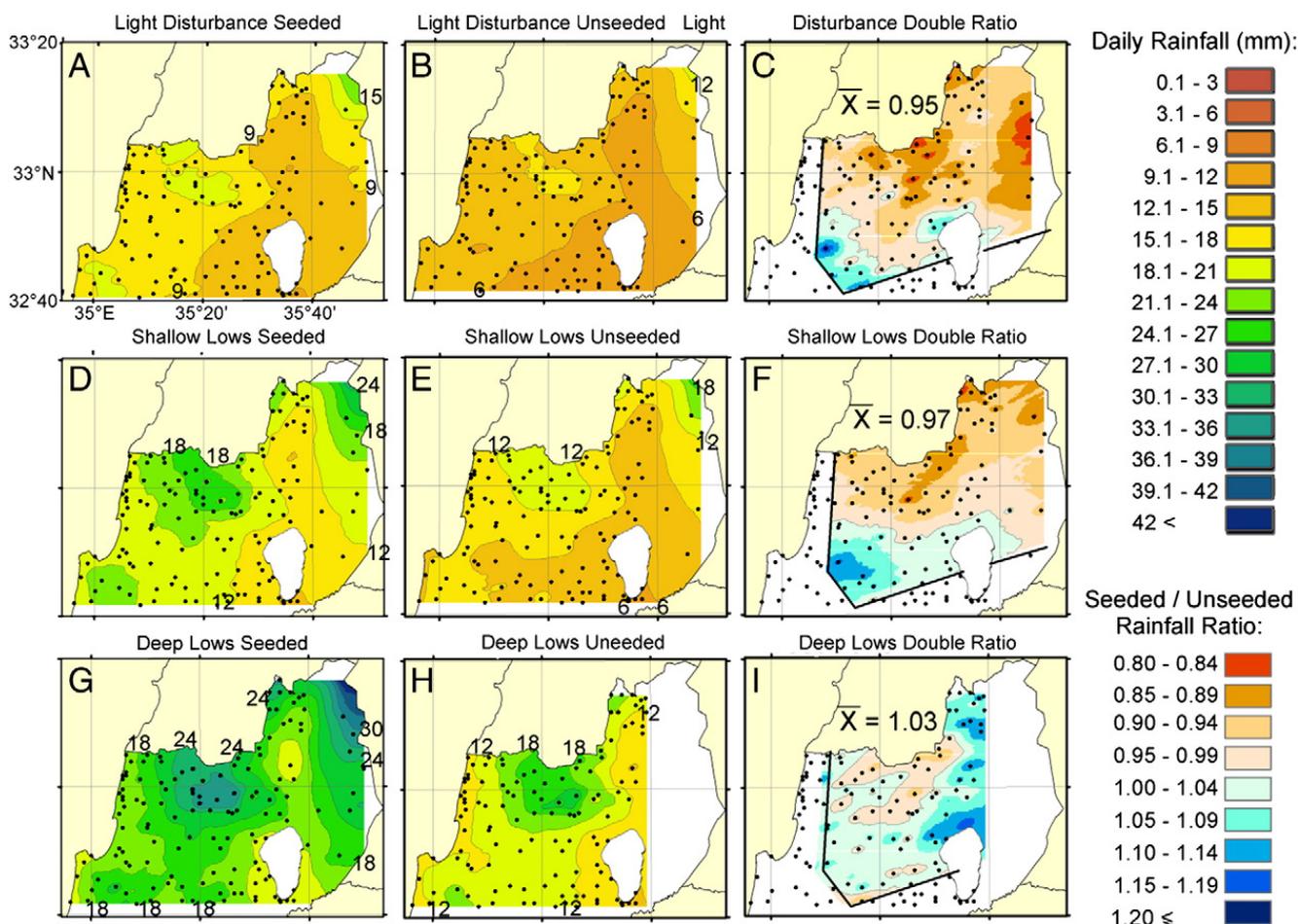


Fig. 6. The spatial distribution of rainfall and DR for seeded and unseeded days as a function of the synoptic conditions for the Full Period. Note that during light weather disturbances (light rain) and shallow lows, relatively large amounts of rain fell closer to the coast especially on seeded days. The DR is generally < 1.0 , except for areas immediately downwind of the urban areas. Under deep lows, with heavier rainfall, the maximum rainfall shifts eastward and the maximum DR appears near the Sea of Galilee. The average value of the DR is only 1.03. The missing values of DR for the deep lows in Golan Heights (east of the Sea of Galilee) are due to the lack of enough data for unseeded days in this area.

As done above (Section 3a-iii), we averaged the wind speed in all the seeded and unseeded days, regardless of the daily rainfall amounts and compared it to another average of the wind speed weighted by the daily rainfall amounts in the research area (Fig. 5C). In addition, in order to understand the influence of wind speed and cyclone depth on the spatial distribution of rain in the study area and to search for differences between seeded and unseeded days under the same synoptic conditions, we mapped the mean daily rainfall for seeded and unseeded days and the mean DR in the study area. For this purpose the same procedure described in Section 3b was followed, but separately for each of the three categories of cyclone depth as defined in Section 3c (Fig. 6).

e. Comparing seeding in Israel II with an unseeded adjacent equivalent area

In order to estimate the effect of the seeding during Israel II we compared the results on the same exact days with the rainfall in central Israel, located about 100 km to the south of the target and control experimental areas. The stations that were selected contain all the stations in the IMS archive that fulfill the following criteria:

- The number of rain days during the corresponding period to Israel II is large enough such that the standard

error on the seeded and unseeded days does not exceed 12% of the average daily amount (see expanded discussion in Section 3a-ii above).

- Stations that are equivalent to those in the target area in the north, namely stations that are between 0–8 km from the seashore were used as the control area and stations that are farther than 20 km from the seashore as equivalent to the target area in the north. The rainfall amounts for stations in central Israel were calculated and mapped in the same way as those in the north, see Fig. 7. The definition for seeded and unseeded in both areas relies on the allocation of days for the northern area in the experiment logbook of Israel II.³

³ It should be noted that during Israel II, seeding along the coast of the central region of Israel was also carried out. In fact, days that were not seeded in the north were seeded in the center. However, the seeding line was west of the coast, thus eliminating the possibility of having a control area on the coast. The effect of seeding in this area was discussed by Gabriel and Rosenfeld (1990) and Rosenfeld and Farbstein (1992, pg. 722) who concluded that cloud seeding in this area was not effective at all.

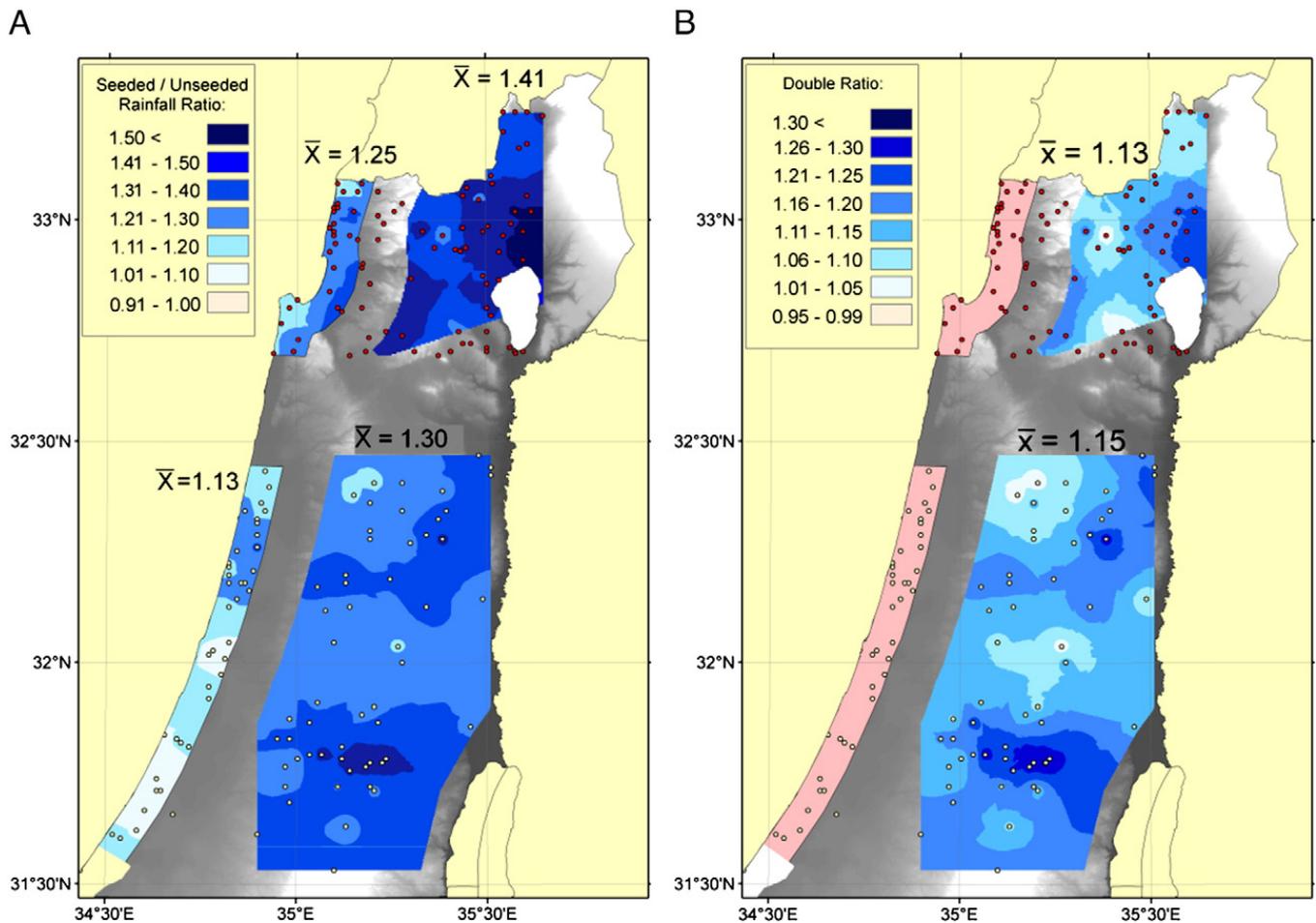


Fig. 7. Seeded/unseeded daily rainfall ratio and DR during “Israel II” experiment in the experimental area (northern Israel) and in a reference area (central Israel). (A) Rainfall ratios distribution and spatial means of this ratio in the control and target areas in northern Israel and the equivalent strips in the reference area of central Israel. (B) The DRs in the target area in the north and in the center are obtained by dividing the mean of the seeded/unseeded values in the north target (1.41) by the value in the north control (1.25) and the corresponding values in the center (1.30 divided by 1.13).

4. Results

- a) The daily rainfall amounts on the seeded and unseeded days

Fig. 3A–C presents the average rainfall amounts in the research area on Israel II on seeded and unseeded days and the values of the DR between each target station and the control area, following the method used in the original experiment. From the figure it becomes clear that in spite of the effort to obtain some balance between the seeded and unseeded days during Israel II experiment, there are significant differences of the rainfall characteristics in both target and control areas. The ratio between the average rainfalls during seeded to unseeded days for the control area alone was 125% (about 12.3 mm daily amount on seeded days to 9.9 mm for unseeded days). In the target area this ratio was even larger (around 140%), thus the DR in the target area was greater than 1, with a spatial average of 1.12 and a range between 0.95 in the North West corner to 1.25 in the east (Jordan valley).

In Fig. 3D–F we present the results of the experimental days based on the correction and filtration criteria set in Section 3a above. It shows that the results presented in Fig. 3A–C were not only maintained but amplified.

Following the elimination of days with very little rain (whose contribution to the total amount of rain was minimal), the total amounts of the daily rainfall in both seeded and unseeded days were calculated. The ratio of the daily rainfall on the seeded/unseeded in the control area was 131% (14 mm on seeded days and 10.7 mm on unseeded days). In the target area the increase was even greater. This led to an increase in the value of the DR to 1.17 and even to some extreme values of 1.31–1.35 in the eastern stations. It is important to stress that the changes in the methodology used here enhanced the differences between seeded and unseeded days and increased the value of the DR; however, it did not change the spatial distribution, as can be seen from Fig. 3C and F.

Examining the differences in the daily amounts on seeded and unseeded days for the Full Period and the values of the DRs (Fig. 3G–I) provides a completely different picture from that obtained for the Israel II period. While in Israel II the DR was of the order of 1.12–1.18, in the Full Period the ratio between the rainfall on seeded and unseeded days in the target area was very similar to that in the control area. Thus the DR was exactly 1.00.

In the Full Period used here, the amount of rainfall on the seeding days was significantly higher than on the unseeded days. But in contrast to Israel II in which seeding days were selected randomly, in the operational period seeding was done mostly on days with heavier rainfall. In other words, most of the days with small rainfall amounts were added to the unseeded days, thus leading to lower mean rainfall amounts on unseeded days in both control and target areas. The extension of the research period from the period of Israel II to the Full Period did not only reduce the spatial mean of the DR for the target area to 1.00 but also reduced its range of values from 0.98–1.30 in Israel II to 0.95–1.05 over the Full Period. Even the spatial variation that was apparent in Israel II disappeared with the extension of the research period. Similarly, the increase in DR in the eastern part of the target area during Israel II disappeared and dropped from 1.30 to ~1.00.

- b) The ratio of rainfall between cluster stations in the target and control areas during the full research period

Using the clusters method (see the [Method of analysis and procedure section](#)) we found again a dramatic drop of the DR values from 1.20 during Israel II to 1.00 in the Hula Cluster and even to smaller values in the Upper Galilee clusters (see Fig. 4A). Computing the ratios between the cluster stations in the target and control areas on seeded and unseeded days for cumulative rainfall amounts that are equal to that accumulated amounts during Israel II reveals that the ratios are variable and not robust (Fig. 4B–D). The results presented in Fig. 4B–D show that even after accumulation of more than 1600 mm of rainfall in the control area the ratio target/control on seeded days varied between 0.74 to 0.96 in the Hula valley, 1.03 to 1.3 in the eastern Upper Galilee and 1.31 to 1.50 in the western Upper Galilee. On the unseeded days the ratio varied less –0.82 to 0.90 in Hula Valley; 1.15 to 1.33 in the eastern Upper Galilee; 1.38 to 1.44 in the western Galilee. During the period of Israel II in which seeding was chosen randomly, the ratios target/control reached higher values than at any other segment of time during the Full Period. These high values resulted in high DR values in the three clusters. It is important to note that a small shift of the time window from the experimental period (1969–1975) to the beginning of the operational seeding period (1975–1978) leads to a sharp decrease in the ratio between the three target clusters and the control on seeded days (see Fig. 4B–D), and a corresponding decrease of the DR to 1.00 and even smaller values.

The average ratio of target/control for all the clusters for the unseeded days shows slightly higher values than those for the seeded days. This explains why the values of the DR for the Full Period in the three clusters varied between 1.00 and 0.95.

- c) Differences in synoptic conditions between seeded and unseeded days during Israel II and the Full Period

In light of the results of the last section showing that the DR target/control was significantly greater than 1.00 only during Israel II experiment we decided to investigate whether there are other factors that could produce higher precipitation over the inland area (target) as compared to the coast (control) on the seeded days. One of the factors is the timing of the rain with respect to the

rainy season and the other is the wind speed at low levels during the rain storm. We investigated this factor by analyzing the depth of Eastern Mediterranean cyclones and by radio-sonde measurements.

Inspection of the differences in the timing within the rainy season of the seeded and unseeded rainy days showed no detectable differences during Israel II or during the Full Period. An approximately equal number of seeded and unseeded days occurred before and after the 16 January ± 1 day. Thus the timing of the seeding during the season could not be the reason for the high DR values in Israel II or for their decrease in the Full Period. A close look at the synoptic conditions revealed that in Israel II the frequency of low pressure systems was higher on seeded days than on unseeded days. Fig. 5A shows that in 41% of the seeded days during Israel II the area was affected by deep lows, which resulted in 50% of the total rainfall on the seeded days. In contrast, on the unseeded days only 28% of the days were associated with deep lows in which only 37% of the total rainfall was accumulated.

It is important to mention that the large differences shown above are much smaller during the Full Period than in Israel II (compare Fig. 5A 3–4 to B 3–4). For example, during the Full Period the difference in total rainfall associated with deep lows between seeded and unseeded days was 3% (42% as compared to 45%) while during Israel II the difference was 13% (see Fig. 5A–B).

The differences in the distribution of the synoptic and pressure systems that were linked to the seeded and unseeded days are also visible in the average wind at 850 hPa level (see Fig. 5C). It is clear that the wind speed on seeded days in Israel II was stronger than on unseeded days (19.2 m/s as compared to 15.9 m/s, $\sigma = 7.6$ m/s). In contrast, in the Full Period, the difference in the wind speed between seeded and unseeded days was smaller than in the random Israel II experiment. This last result appears in spite of the fact that during the Full Period days with light rain that are associated with lighter winds were intentionally not seeded. It should also be mentioned that the differences in the wind direction between seeded and unseeded days were small.

Using the three types of synoptic situations (light disturbances, shallow lows and deep lows) we can calculate the spatial distribution of average daily rainfall and the corresponding DR for each of the three types separately (Fig. 6). It is clear that the values of the DR under conditions of deep lows are higher than for the other two cases, but still it is very close to the neutral value 1.00 (mean DR in the target area – 1.03). Under conditions of light disturbance the mean DR in the target area is below 1 (0.95–0.97). A possible positive effect of seeding in this type of synoptic condition ($DR > 1.0$) is confined to a small area located immediately downwind of the control area and downwind of the urban area of Haifa.

- d) The DR of rainfall in central Israel

Since differences in synoptic conditions were found between seeded and unseeded days in the north of Israel, it was interesting to investigate whether such effects would be seen in central Israel, in which some seeding off the coast

was done during Israel II but in which no seeding was carried out during the operational period.

In Fig. 7A we show the rainfall ratios between seeded and unseeded days of Israel II in northern Israel and the equivalent ratios in the center of Israel.

From the figure it is clear that almost all the values of the ratios are larger than 1.00, both in the north and in the center. Note that the ratios in the north target and control areas are higher than in the corresponding target and control in the center. The values of the DR obtained by dividing the ratios on the inland-hills with the ratios on the coast, are slightly higher than the corresponding DR values in the north (Fig. 7B), where intentional intensive seeding has been carried out for the past 40 years.

5. Discussion

The results of the re-analysis of Israel II experiment based on our data (Fig. 3A) show similarity to those of Gagin and Neumann (1981). The DR obtained is 1.12 for the area to the east of the seeding line, as compared to 1.13 in Gagin and Neumann (1981). Also spatially, the agreement between our results and those of Gagin and Neumann is almost perfect where the highest DR (1.26) is located in the eastern end of the target area. In this area, the Hula Valley, no orographic lifting occurs. This is in contrast to the work by Givati and Rosenfeld (2005) who argue that the maximum efficiency due to seeding takes place in the orographic clouds over the Galilee.

The agreement between the present analysis and that of Gagin and Neumann is complete except for the average rainfall amounts on the seeded and unseeded days, where our values are higher in both target and control areas. The strong consensus between the present results and those of Gagin and Neumann (1981) supports the DR calculations of Israel II. But the lack of enhancement observed in the examination of the Full Period stresses that the robustness of the DR values in Israel II does not mean that the Israel II enhancement of rainfall was due to seeding.

An important result of this study is the comparison between the seeded area in the north and the unseeded area in the center of the country. As is shown in Fig. 7A and B the center of Israel during the seeded days of Israel II in northern Israel received high amounts of rainfall both in the inland and coastal areas. This result is in agreement with Rangno and Hobbs (1995) who showed that during Israel II, increases in rainfall were also observed in Lebanon, north of the target areas in the Galilee. It is interesting to note that the DR between the inland and coastal areas in the center of the country was found to be slightly higher than in the north, suggesting that under the best scenario, the seeding had no effect on the rain amount. These findings are close to those of Gabriel and Rosenfeld (1990) who showed that a detailed analysis of the original plan of Israel II does not provide any solid proof that cloud seeding enhanced the precipitation in the seeded areas.

The method used to perform the present stratification in which days allocated for seeding but where no seeding occurred were classified as unseeded, actually increased the DRs (Fig. 3F). Thus one cannot blame the method used

here as the cause for the lack of rain enhancement by seeding during the Full Period (Fig. 3I).

The decrease in the effects of seeding in the period that follows Israel II has been published before by Nirel and Rosenfeld (1995) who reported that the effect of seeding during the early operational period (1976–1990) was only 6% as compared to 13% during the experiment. Kessler et al. (2006 in Hebrew) and Sharon et al. (2008) extended the analysis of the operational period to 2002 and found that the DR showed no enhancement during the seeded days. Fig. 4 shows that the ratio of rainfall decreases with time but not in a consistent and continuous way. This is inconsistent with the argument presented by Givati and Rosenfeld (2004, 2005) who argued for a consistent suppression by pollution of the ratio of rainfall between the target and control in the north of Israel. Even if one ignores the high frequency variations between the target and control and looks for the longer trends, it is difficult to identify a continuous decreasing trend between the target and the control. In Fig. 4 one can see that in the early research period before seeding even started, the ratio between the cluster stations in the Hula Valley and the Galilee areas (target) to the cluster near the coast (control) increased continuously and reached a peak during the experimental period of Israel II.

After Israel II, during the operational period, the ratio decreased somewhat, especially on the lee side (eastern side) of the Galilee Mountains. Looking at the whole research period, it is difficult to identify a significant decrease in the ratio, except for a decrease in the ratio between the eastern cluster of stations and the control area near the coast, as was found by Alpert et al. (2008) and Halfon et al. (2009).

The question of why during Israel II the DR was high and then dropped was investigated by looking at the differences of the timing of seeded and unseeded rainy days along the rainy season, the depth of the low pressure systems and the wind speed at 850 hPa. Changes in the rainfall amounts between the coast and inland during the rainy season occur due to the differences between sea surface and land temperatures during the winter months and the effects of orographic lifting inland. Early in the winter season, the rain falls more along the coast due to the convective activity produced by convergence resulting from the temperature gradient between the sea and the land. Later on, as this coastal gradient decreases, the clouds precipitate less over the coast and the orographic enhancement of the rainfall is more pronounced (see Goldreich, 2003; Khain et al., 1993; Khain and Sednev, 1996). For this reason, differences in timing of the rainy days could contribute to artificially high (low) DR values if the seeded days were more concentrated in the last (first) part of the season. However, examination of the differences in the distribution of seeded and unseeded days during the season showed no significant differences between them.

On the other hand, examination of the strength of the wind speed at 850 hPa and the depth of the low pressure systems shows noticeable differences between seeded and unseeded days (Fig. 5) that could explain at least in part the decline of the DR values between Israel II and the Full Period. On seeded days during Israel II the wind speed was

noticeably higher and the depth of cyclones was stronger than on unseeded days. Examination of the changes in the mean daily rainfall and its spatial distribution as a function of the cyclones' depth (compare Fig. 6A, D, and G) reveals that deeper disturbances associated with stronger winds lead to enhanced precipitation. Combining our findings with those of Saaroni et al. (2009), who showed the connection between the depth of the low pressure systems and the precipitation amounts in Israel, especially in inland and mountainous areas, one can see why the seeded days in Israel II were much rainier in the inland areas than the unseeded days, leading to higher DR values.

This last point becomes even clearer when we examine the spatial distribution of the DR as a function of the depth of the synoptic conditions (Fig. 6). Deeper disturbances are associated with stronger winds and thus prolong the rainy events, leading to enhanced precipitation on the eastern side of the Galilee Mountains and to higher DR values. The apparent higher values of DR in deep lows as compared to those in shallow lows suggest that seeding may have had a small positive effect on rainfall in the former cases and negative effects in the latter. However, it is important to note that the mean DR values for the target area in all three cases are close to the neutral value of 1.00, implying that seeding had very little impact on rainfall regardless of the depth of the synoptic conditions. These low values of DR are in agreement with those of Kessler et al. (2006) and Sharon et al. (2008), although they found small but opposite trends⁴ in which the rainfall in the target area increased a little under conditions of low daily precipitation rates (>5 mm/day) and decreased a little under conditions of high daily precipitation rates (>15 mm/day). However, in both cases the significance of the results was very (see table 6.14 in Kessler et al., 2006).

6. Conclusions

Re-analysis of the cloud seeding experiment and operations in Israel shows that seeding has not produced the expected enhancement in rainfall. Comparison of the DR in the seeded area with that in an unseeded adjacent area to the south, showed no difference with even slightly higher values in the unseeded area. This suggests that seeding had little or no effect on total precipitation on the ground. These results are in agreement with those presented by Rangno and Hobbs (1995), and the DR calculations of Kessler et al. (2006) and Sharon et al. (2008).

Furthermore, it is shown that the high DR values obtained during Israel II experiment were largely due to synoptic conditions in which deep low pressure systems and stronger winds occurred more frequently, leading to more efficient penetration of rain clouds inland and providing better conditions to the evolution of orographic rain.

⁴ Kessler et al. (2006) checked the contribution of seeding in three different cases of daily rainfall amounts which are equivalent somewhat to the three different synoptic cases examined in this study.

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Appendix A

A.1. Computing daily rainfall amounts in the control area for the 2389 days of the study period

In order to use the control area as a reference for estimating the daily natural rain amount in the study period, we computed the daily values by averaging the measured values in the 35 stations of the control area. Since not all the 35 stations operated on each of the 2389 days the daily rainfall in each specific day was calculated based only on the stations that operated on that day. This procedure can create some bias because the daily mean in this method could be affected not only by the natural productivity of the clouds, but also by the location of the stations operating on each day. In order to overcome this difficulty, we multiplied the daily average rainfall by a factor we call Wetness Factor. This factor examines the Wetness of the stations that are operating on a specific day (based on the 1961–1990 annual rainfall averages) in comparison to the average wetness of all the 35 stations (see Eq. (A-2)).

In this way on days in which the operating stations happen to be in a region of high rainfall, the Wetness Factor is larger than 1 and the opposite is true on days in which the stations are located in a region with low precipitation amounts.

$$\bar{X}_{ci} = \bar{x}_{ci} / (\bar{x}_{msi} / \bar{x}_{mS}) \quad (A-1)$$

\bar{X}_{ci}	Corrected rainfall spatial mean in the control area on a specific day
\bar{x}_{ci}	The spatial mean of the rainfall in the control area on a specific day based on the operated stations on that day.
\bar{x}_{msi}	Average of the mean annual rainfall values of the operated stations
\bar{x}_{mS}	Average of the mean annual rainfall in the 35 control stations.

The same equation was used in the cluster method for adjusting the daily mean rainfall in each of the 4 clusters. At this time the parameter “c” represented the cluster area and \bar{x}_{mS} represented the spatial average of the mean annual rainfall in all the stations that make up the cluster.

A.2. Calculating the average rainfall for seeded and unseeded days in each of the stations in the study area

Following the procedure above, we obtain a full set of daily rainfall values in the control area from which the average daily amount was computed for the seeded and the unseeded days. After obtaining the full daily dataset for the

control area and computing the mean daily amount during seeded and unseeded days for the whole study period, it became possible to compute the mean daily amount in each of the stations in the study area.

The method for calculating mean rainfall amounts in seeded and unseeded days (*Ris*, *Riu*) for the whole study period in stations with partial data is described by:

$$\begin{aligned} \text{a. } R_{is} &= (ris / (r\bar{x}s)) * R\bar{x}s \\ \text{b. } R_{iu} &= (riu / r\bar{x}u) * R\bar{x}u \end{aligned} \quad (\text{A} - 2)$$

where

<i>i</i>	Specific station
\bar{x}	Spatial daily mean in the control area
<i>R</i>	Mean daily rainfall for the Full Period
<i>r</i>	Mean daily rainfall during the measured days in station <i>i</i> .
<i>s</i>	Seeded days
<i>u</i>	Unseeded days

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