Q. J. R. Meteorol. Soc. (1988), **114**, pp. 495–513 551.574.1:551.577.11 (569.4)

Rain from clouds with tops warmer than −10 °C in Israel

By ARTHUR L. RANGNO
(Communicated by Professor Peter V. Hobbs)
Atmospheric Sciences Department, University of Washington, Seattle, U.S.A.

(Received 14 January 1987; revised 30 September 1987)

SUMMARY

Rawinsonde observations combined with surface synoptic reports and satellite data, indicate that in Israel rain often falls from clouds with top temperatures ⩾ −10 °C. This suggests the presence of relatively large cloud droplets and/or high concentrations of ice particles at these temperatures, and a relatively efficient natural precipitation-forming process.

1. INTRODUCTION

Clouds over Israel are of particular interest because this is one of the few regions in the world where cloud seeding has apparently increased precipitation (e.g. Gagin and Neumann 1974, 1981). It has been indicated that this is because the clouds in this region are inefficient natural rain producers when their top temperatures are ⩾−21 °C (Gagin 1971; Gagin and Neumann 1974, 1981; Gagin 1975).

In this paper we describe the results of an examination of thirty months of rawinsonde data for a site in Israel. This study indicates that rain often falls from clouds with top temperatures ⩾−10 °C and at times from clouds with tops as warm as 0 °C.

2. DATA SOURCES AND METHODS OF ANALYSIS

Thirty months of rawinsonde data during the rainy winter season, obtained from the Israel Meteorological Service (IMS) site at Bet Dagan (Fig. 1) were used to estimate the cloud top temperatures at which rain fell. The periods examined were January through March 1978, November through March 1978–79, 1979–80, 1980–81, 1983–84 and 1984–85, and January and February 1986. These months were chosen because, with the exception of the two months in 1986, three or four rawinsondes per day were launched by the IMS.

Rawinsonde launch times from Bet Dagan during seasons with four soundings per day were 0430, 1030, 1730, and 2230 GMT. During months with three soundings a day, launches were routinely made at either 0430 or 1730 GMT, and at 1030 and 2230 GMT. For months with two soundings a day, launch times were near 1030 and 2230 GMT.

A sounding was associated with rain if rain was reported to be falling at, or fell within an hour of, the closest synoptic observation time after the rawinsonde launch. IMS surface synoptic observations are made at the usual times (12 GMT and at three-hour intervals). In the worst case, when rain began exactly at the time when the synoptic observation was made, the rain could have occurred as much as 90 minutes after the beginning of the sounding.

The synoptic stations used were those within 20 km of the Mediterranean coastline. This was done to avoid effects due to cloud seeding. Operational cloud seeding has been conducted in Israel since the winter of 1975–76. This seeding consists of silver iodide releases from the ground upwind of the hill regions of Har Meron in the north to Jerusalem in the south, and from aircraft that fly a north–south track immediately offshore

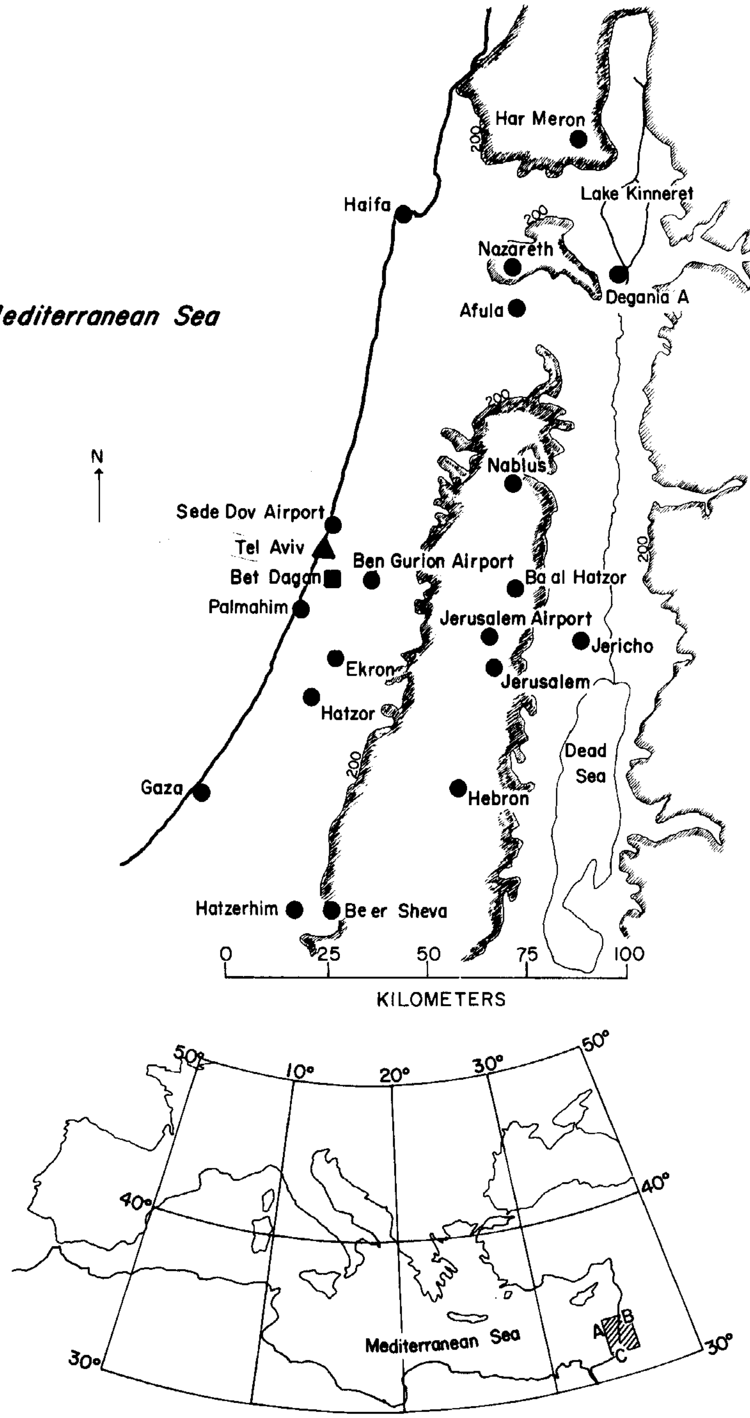

Figure 1. Map of northern Israel showing the synoptic stations examined in this paper. The coastal stations are Sede Dov Airport, Bet Dagan, Palmahim, Gaza, Ben Gurion Airport, Ekron and Hatzor. The rawinsonde launch site is at Bet Dagan, denoted by a square. The triangle denotes a former radar site at Tel Aviv. The 200 m contour is shown by partial hatching. Hatched portion of lower inset map shows location of the region under consideration.

or over the Israel coastline, and it may occur anywhere from about Haifa in the north to south of Gaza in the south. The actual portion of the coastline flown along varies with the wind direction and cloud cover present. The silver iodide is released from the aircraft at cloud base, usually about 0·8 km above sea level.

Neither aircraft seeding nor ground seeding could affect precipitation at stations on the coastline (such as Sede Dov Airport, Palmahim and Gaza) nor at Bet Dagan, which is only 8·5 km inland, since it is virtually impossible for the silver iodide to rise up to activation levels (around -10 °C), grow into precipitation elements and then fall on these locations with any reasonable westerly wind.

For stations such as Ben Gurion Airport, Ekron and Hatzor, which are 10–15 km inland, precautions were taken in the present analysis to exclude possible seeding effects. For example, in light westerly flow, it is conceivable that aircraft seeding might affect these stations. Therefore, when cloud tops were colder than -5 °C (the temperature at which activation by silver iodide is possible), mean wind direction and wind speed criteria were invoked to exclude these cases. Thus, with westerly (220° clockwise to 320°) winds at 850 and 700 mb, the average wind speed had to be $\geq 7{\cdot}5\ \mathrm{m\,s^{-1}}$ for a case to be included in the present analysis.

It should also be noted that the clouds of interest here are those from which precipitation fell when the cloud top temperature was ≥ -10 °C. According to Gagin and Neumann (1981) and Gagin (1975), clouds with tops as warm as this do not respond to seeding. Further, Gagin and Neumann (1981) have reported that increases in ice particle concentrations in clouds, due to seeding, are not observed within 20 km downwind of the aircraft-seeded track. Thus, for these reasons, as well as the precautionary measures described in the previous paragraph, it is unlikely that the rain that fell in the coastal region from the clouds that we will consider was due to seeding.

Winds with an easterly component at 850 or 700 mb during rain situations, a rare occurrence in Israel, are not considered in this analysis.

Four types of sounding were found to be associated with rain. These are shown in Fig. 2. Three of these types, shown in Figs. 2(a) to 2(c), involve air masses with conditionally unstable lapse rates through a great depth. In these cases it is difficult to obtain accurate assessments of cloud top temperatures using radiosonde data, and we have not attempted to do so here.

A fourth type of sounding, shown in Fig. 2(d), is associated with clouds that are capped by a substantial stable layer, a situation that occurs most often between major storms or near the end of a rain spell. For this type of sounding we have assumed that the cloud top is located at the base of the stable layer. It will be seen that even if the cloud top temperature was as much as 5 degC lower than the value obtained in this way, it would not alter the main conclusions of this paper.

Criteria were used to make reasonably sure that a stable layer was persistent and deep enough to cap the underlying convection. These criteria were: the base of the stable layer had to be at or below 600 mb; the stable layer had to be $\geq 0{\cdot}5$ km thick and had to be present on the next sounding (most of which were no more than 5–7 h after the first sounding and never >13 h later); and the temperature–dew-point spread above the moist layer had to be ≥ 15 degC ($\leq 30\%$ relative humidity). Soundings that met the stability criteria but were not followed by another type 2(d) sounding when rain was falling were included in the type 2(c) group.

A stable layer is defined here as one over which the average lapse was less than or equal to one half that of the pseudo-adiabatic lapse rate. As a result of imposing a minimum criterion for the depth of a stable layer, the mean depth of the stable layers capping the clouds in the type 2(d) category was 1·1 km.

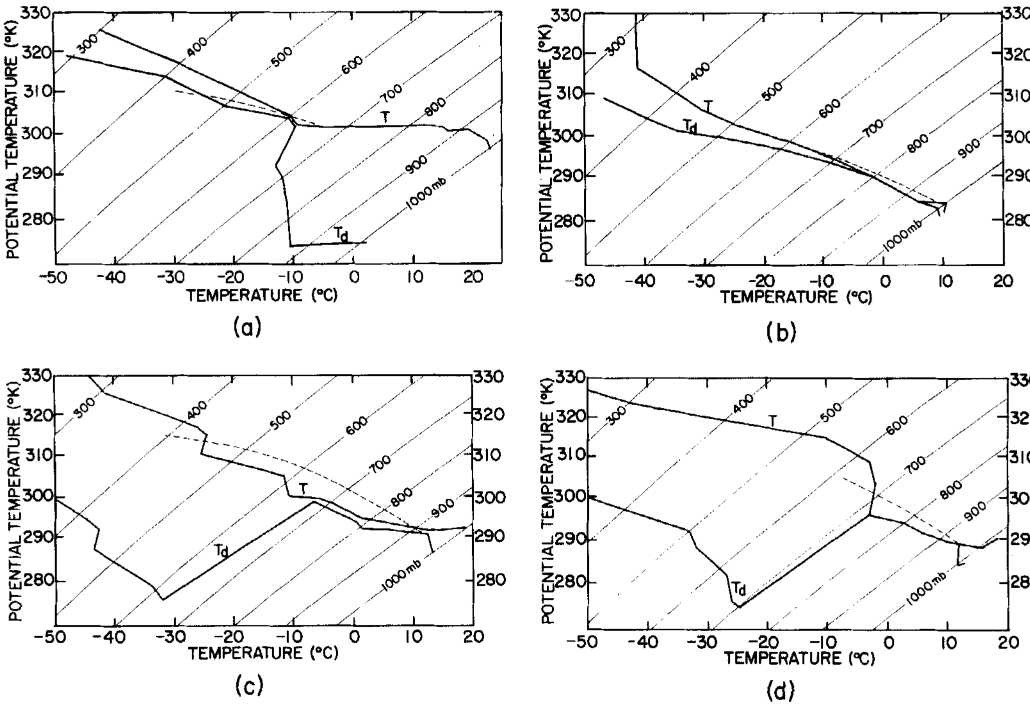

Figure 2. The four types of rawinsonde soundings associated with rain in Israel plotted on a temperature–entropy diagram. (a) Type 2(a), which often precedes frontal passage, is comprised of thick middle- and high-level cloudiness. (b) Type 2(b) is deeply moist and unstable in which thunderstorms often occur. (c) Type 2(c) is highly unstable, but the moisture top is below 600 mb. (d) In type 2(d) the moisture top is below 600 mb and it is capped by a strong stable layer. Pseudoadiabats are indicated by dashed lines, pressure surfaces, in millibars, by sloping fine solid lines and temperature (T) and dew-point (T_d) soundings by heavy solid lines.

One exception to the above rules was permitted: a cloud top temperature from a single type 2(d) sounding associated with rain was used if the following sounding was not associated with rain, and was also so dry that the presence of clouds could not be inferred from it. In these cases it was observed that the initial capping stable layer had weakened, usually in conjunction with daytime surface heating. In these 'tail end' situations, it is assumed that the clouds dissipated rather than grew deeper as drying occurred.

Also, the air masses bringing rain to Israel in the wintertime are nearly always of polar origin and the equivalent potential temperatures associated with these air masses are quite low, usually <315 K. Hence, the latent heat release associated with cloud development in Israel is quite limited (about half that available during the warm season in the eastern half of the United States). Consequently, deep stable layers in Israel are much more likely to produce a well-defined lid on convective clouds.

In support of the contention that accurate cloud top temperatures can be derived from type 2(d) soundings, we note that Hill (1982) reported a correlation of 0·83 between cloud top heights measured by a vertically pointing 8·6 mm (K_a band) radar and those heights derived from rawinsondes. In arriving at this rather high correlation, Hill did not stratify the soundings by the moisture and stability characteristics, as has been done here. Hence, we believe that the cloud top temperatures in the capped type 2(d) soundings category are quite accurate.

Finally, METEOSAT-derived average cloud top temperature data are available at rawinsonde launch times for two of the case studies discussed in section 4. Three 200 km-square regions over and around Israel were used. The first region, marked A on Fig. 1, is centred about 150 km off the northern Israeli coast. In both of the case studies where satellite data are available, region A is upwind of the rawinsonde site at Bet Dagan. Region B includes the mountainous terrain of extreme northern Israel, extreme southern Lebanon, and extreme south-west Syria. Region C is located along the extreme southern coastline near Gaza.

3. Results

Table 1 summarizes the results of analysing 432 rawinsonde soundings associated with rain at the launch site, Bet Dagan, or at nearby stations, for the three dominant sounding types (types 2(b), 2(c) and 2(d)). (Type 2(a), which is associated with <4% of the rain occurrences and involves mid-level clouds, is not included.)

Strongly-capped soundings (type 2(d)) associated with rain occurred on about one quarter of all occasions when rain fell at Bet Dagan or nearby sites in Israel. Both the median and the mean cloud top temperatures derived from these soundings are −5 °C. Eighty-nine out of the ninety-eight type 2(d) soundings analysed had cloud top temperatures ⩾−10 °C.

TABLE 1. Summary of rawinsonde sounding types (see Fig. 2) associated with rainfall at Bet Dagan, Israel, and/or nearby coastal stations, during the rainy season of November through March.

Season	Number			Mean cloud top temperature, (°C), for type 2(d)
	type 2(b)	type 2(c)	type 2(d)	
Jan.–Mar. 78	18 (49)	9 (24)	10 (27)	−5
Nov. 78–Mar. 79	32 (43)	21 (28)	22 (29)	−4
Nov. 79–Mar. 80	43 (39)	45 (41)	22 (20)	−8
Nov. 80–Mar. 81	27 (42)	27 (42)	11 (17)	−3
Nov. 83–Mar. 84	27 (41)	25 (38)	14 (21)	−6
Nov. 84–Mar. 85	13 (34)	16 (42)	9 (24)	−6
Jan.–Feb. 86	10 (38)	6 (23)	10 (38)	−3
Totals	170 (40)	149 (34)	98 (23)	−5

The numbers in parentheses are the percentages of the sounding type for the indicated season.

The eighty-nine soundings from which rain fell from clouds with tops ⩾−10 °C make up 20% of all of the soundings analysed. Hence, at the minimum, 20% of the clouds with tops ⩾−10 °C in this region gave rain. (This is the minimum percentage because the three other types of soundings, particularly type 2(c), would be expected to contain instances of rain from clouds with top temperatures ⩾−10 °C.)

If a 5 degC cooling is considered, which might be produced by evaporational cooling and by turrets that 'overshoot' by as much as 0·5 km into the deep stable layer above, the mean and median cloud top temperatures for type 2(d) soundings would still be only −10 °C. This cloud top temperature is still 4 degC higher than would be expected for the highest cloud top temperature of any precipitating cloud (based on the presence of ice particle concentrations of ⩾1 per litre) and 7 degC higher than the cloud top temperature where clouds average 1 per litre ice particle concentrations (Gagin and Neumann 1974; Gagin 1975).

Thus, it would appear that precipitation is not unusual from clouds with top temperatures ⩾−10 °C, which corresponds to typical cloud depths of ⩽3 km in Israel.

4. Some case studies

The following case studies are presented for the purpose of illustrating the conditions under which rain can occur over Israel. The measurements to be presented originate with the maps and data of the IMS, although visual observations made by the author are also included. The author was present in Israel from 4 January through 17 March 1986 for this study.

(*a*) *13–15 February 1986*

This was a major storm which began on the evening of the 13th. Altocumulus and altostratus clouds began moving from the south-west during the late afternoon of the 13th. Light rain began to fall by 18 GMT from a deep mid-level overcast of altostratus with scattered to broken stratocumulus and cumulus below. As the rain set in, distant lightning was observed at Palmahim along the coast. This marked the beginning of a 36 h period of intermittent rain and thunderstorms as a broad trough approached and then passed over Israel. Rainfall totals over the next 48 h were generally ⩾40 mm.

The over-water trajectory of the flow in this storm was long, as a blocking upper-level high pressure area over Scandinavia shunted a strong zonal current of the jet stream from the eastern Atlantic across the length of the Mediterranean Sea. Cloud base temperatures and heights were near the normal values of 6–8 °C and 0·7 km a.s.l., respectively (Gagin and Neumann 1981).

Bet Dagan soundings for the concluding 24 h of this storm, beginning with the 23 GMT 14 February 1986 launch, are shown in Fig. 3. The first sounding (Fig. 3(a)) is typical of the deep instability that characterized the rainiest portion of the storm when thunderstorms were common. Cloud tops in the larger cumulonimbus during this period can be inferred to have been above the 500 mb level and at temperatures <−25 °C.

Between 23 GMT 14 February and 11 GMT 15 February, subsidence produced a marked drying aloft as the upper trough moved eastward across Syria and Jordan and a short wave ridge approached. A nearly isothermal layer 0·8 km thick between 635 and 700 mb can be seen on the Bet Dagan sounding for 11 GMT 15 February (Fig. 3(b)). The temperature at the top of these clouds, corresponding to the base of the stable layer, was −8 °C. Indicative of the lowering of the cloud tops and the depth of instability during this period is that the last thunderstorm reported for the region south of a line from Haifa to Lake Kinneret (the Sea of Galilee) was prior to 06 GMT 15 February.

The stable layer continued to strengthen and lower during the next 12 h. Figure 3(c) shows that the base of the stable layer had descended from 635 to 800 mb and had increased in depth to 1 km. Cloud top temperatures were probably no lower than −4 °C at this time.

METEOSAT-derived average cloud top temperatures for the three 200 km-square regions, A, B and C, at 11 GMT 15 February were −3 and 0 °C (bimodal) in region A upwind of Bet Dagan, −12 °C in region B, and −3 °C in region C. Presuming that the usual climatological slope downward in cloud tops (Gagin and Neumann 1974) was present from north (region B) to south Israel (region C), the rawinsonde-derived cloud top temperatures are in good agreement with the METEOSAT average cloud top temperatures.

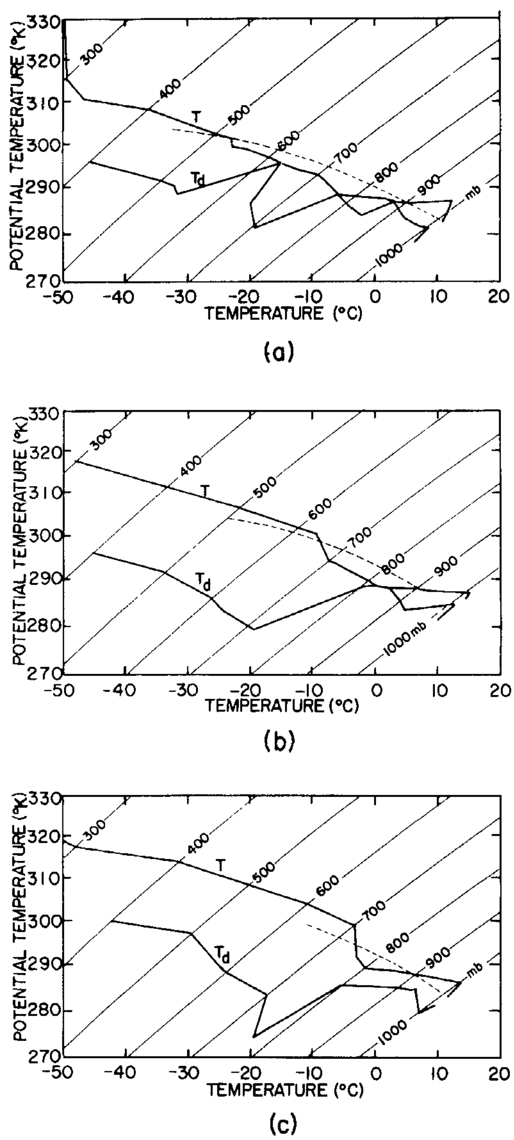

Figure 3. Rawinsonde soundings for (a) 23 GMT 14 February 1986; (b) 11 GMT 15 February 1986; and (c) 23 GMT 15 February 1986.

Most stations in Israel, from the coast to the inland hilly region, reported very light or light ('one dot' or 'two dot') rain on one or more occasions during the 15 h period from 09 GMT 15 February through 00 GMT 16 February as the stable layer developed (Figs. 4(a) to (f)). At Jerusalem, a misty, fine rain fell intermittently from 06 through 22 GMT 15 February from largely overcast skies with stratocumulus and weakly developed cumulus below. Cloud tops, occasionally visible from mid-morning through late afternoon at Jerusalem on 15 February, were flat or lenticular-looking (Fig. 5). Thus, during the last 12 h of this storm, intermittent light rain fell over both coastal and inland central Israel whilst cloud tops were warmer than −10 °C.

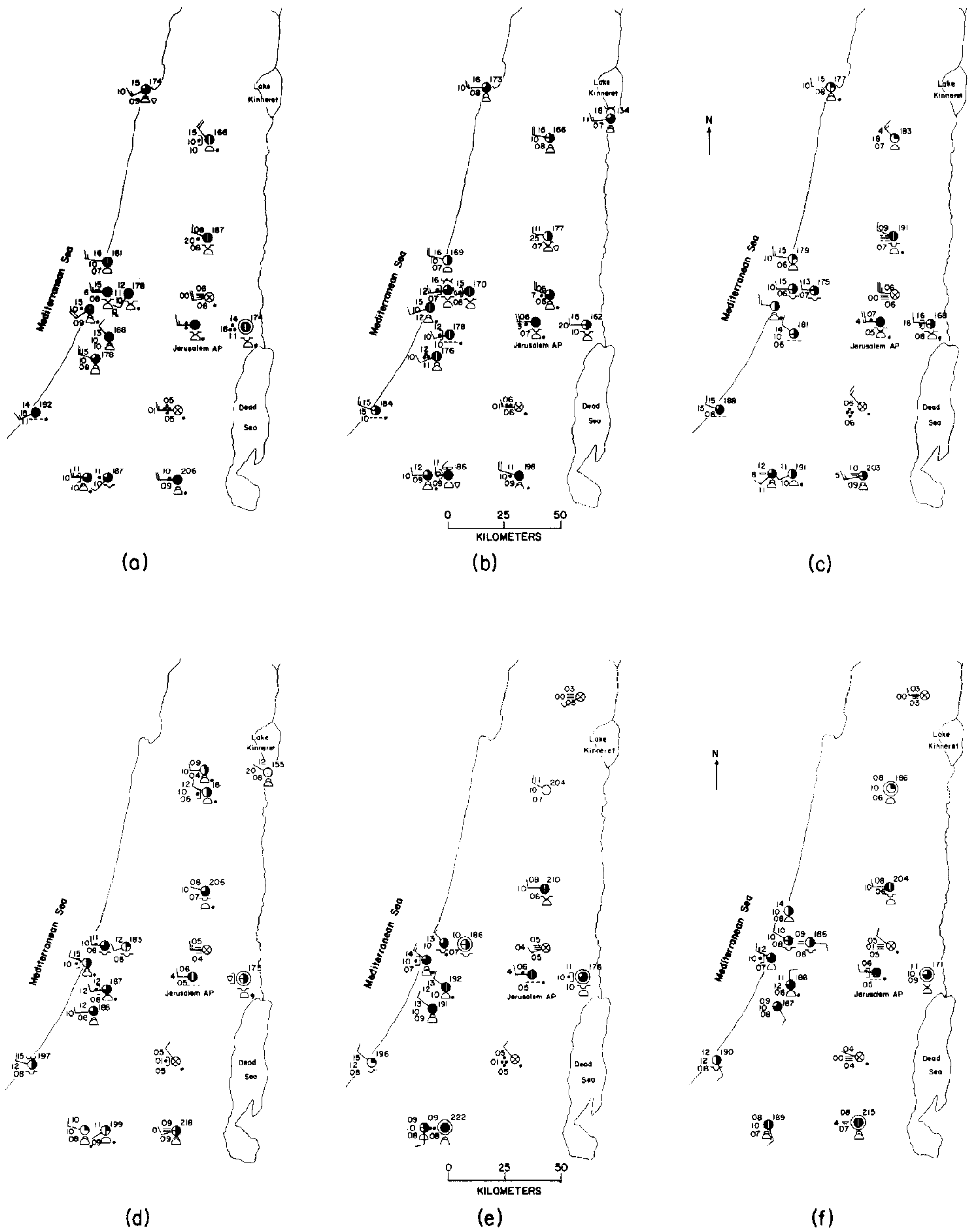

Figure 4. Surface maps for 15 February 1986 at (a) 09 GMT; (b) 12 GMT; (c) 15 GMT; (d) 18 GMT; and (e) 21 GMT; and (f) 00 GMT on 16 February. Standard meteorological symbols have been used.

Winds at 850 and 700 mb were west-north-west at 10 and 16 m s^{-1}, respectively, at 11 GMT and had diminished to 6 and 11 m s^{-1}, respectively, by 23 GMT. These values are such that seeding could not have affected precipitation at stations on the coast or in the coastal plain (see section 2). Thus, the occurrence of rain well upwind of Jerusalen during

Figure 5. Photograph of the tops of a cloud mass that had just produced fine, misty rain in Jerusalem. View is looking eastward from Mt of Olives. The photograph was taken between 1200 and 1353 GMT.

the period when cloud top temperatures were higher than −10 °C suggests that the rain in Jerusalem was not initiated by any cloud seeding that may have been in progress.

This case study illustrates a typical sounding and rain sequence at the end of a major storm which has had a long over-water trajectory.

(*b*) *18–19 January 1986*

A rapidly moving short wave trough passed across Israel during the night of 18–19 January 1986. A cold front, extending from a low pressure centre in Turkey, crossed the country on the evening of the 18th. Because the trajectory of this storm was from north-west to south-east, the over-water trajectory of the air behind the front was fairly short, from western Turkey to Israel, a distance of approximately 600 km.

The storm began with a sudden onset of overcast low cloud and westerly winds that gusted to 15 m s^{-1} during the late evening of 18 January. Drizzle or very light rain began to fall in Jerusalem between 18 and 19 GMT. The rain steadily increased and became showery with sharp showers containing some graupel by dawn of 19 January. The Bet Dagan rawinsonde for 23 GMT (Fig. 6(a)) shows that by that time the air mass could readily support convection up to 650 mb (−12 °C), and probably beyond this level in deeper convective pockets. Thunder was reported at Jerusalem between 06 and 09 GMT 19 January.

Cloud tops noticeably lowered and flattened during the mid-morning hours of 19 January as subsidence produced a strong capping stable layer as the upper short wave trough receded to the east-south-east and an upper-level ridge approached. Scattered lower cumulus built into and enhanced a broken to overcast layer of stratocumulus. During the late morning and afternoon, with the appearance of cloud glaciation, virga and light

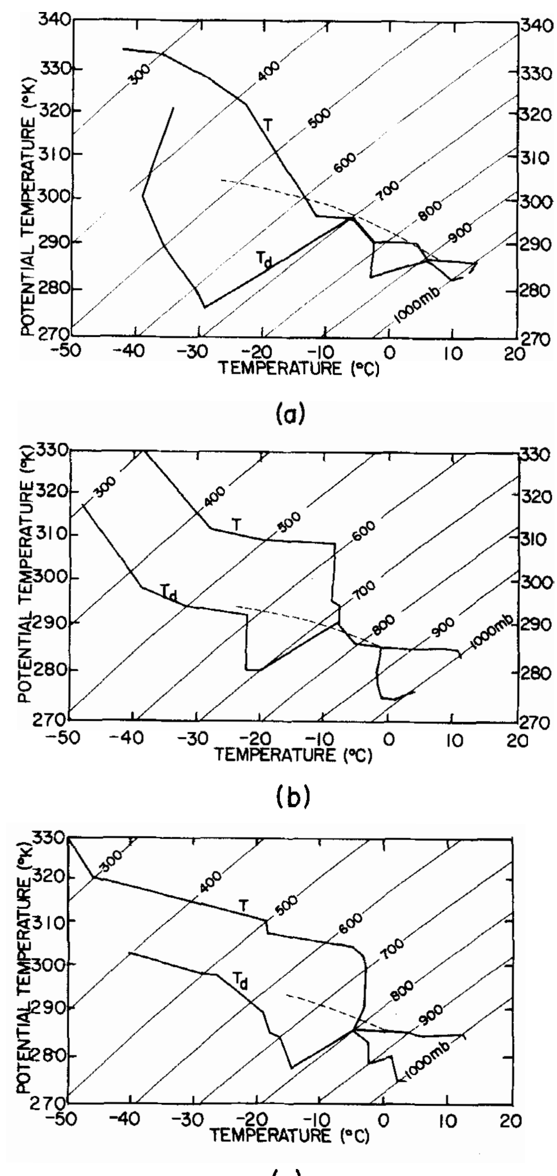

Figure 6. Rawinsonde soundings for 18–19 January 1986. (a) 23 GMT 18 January; (b) 11 GMT 19 January; and (c) 23 GMT 19 January.

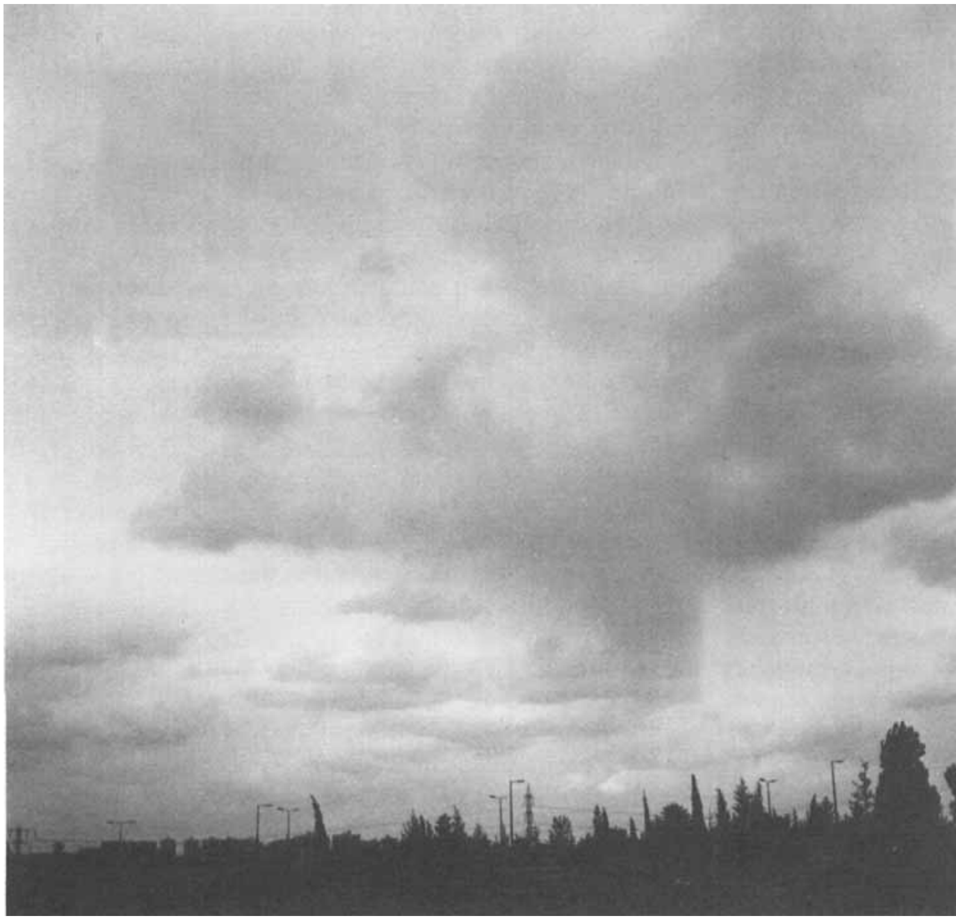

Figure 7. Photograph taken at about 0945 GMT 19 January 1986 of virga and ice crystals partially obscuring cloud bases of cumulus and stratocumulus clouds. View is toward the north-west from Bet Dagan.

precipitation became widespread from these clouds. In some places virga was thick enough to obscure cloud bases, giving the sky an appearance usually associated with altostratus.

Figure 7 shows a photograph of these clouds at the time of and in the direction that a commercial jet entered the clouds on a north-westerly heading. The photograph was taken from the IMS headquarters at Bet Dagan. The pilot reported cloud top at 9000 feet a.s.l. a few minutes later, in good agreement with the radiosonde-inferred cloud top at 720 mb. Note the virga in the centre of the photograph. Mossop and Ono (1969) have reported that when glaciation occurs in clouds, defined by them as the point at which the concentration of ice particles is sufficient to change the appearance of the cloud, it can be assumed that ice particle concentrations of $\geqslant 1$ per litre are present. From flight experience with more recently developed continuous and automatic instrumentation for measuring ice particles, we believe that 1 per litre is a conservative estimate of the maximum ice particle concentrations in clouds having the appearance of those shown in Fig. 7.

Cumulus cloud bases were unusually cold (0 °C) and high (1·5 km a.s.l.) on 19 January (Fig. 6(b)) compared with normal values of 5 to 8 °C and 0·7 km, respectively. This sounding also shows that by 11 GMT cloud tops were limited to 720 mb and about −8 or

−9 °C by a 1·5 km-deep isothermal capping layer. Maximum thickness of the cloud at this time, with cumulus bases at 850 mb and tops at 720 mb, was about 1·3 km. Skies remained broken to overcast stratocumulus, with patchy, modest cumulus below, both sporting virga and glaciation during daylight hours.

Average cloud top temperatures at 11 GMT 19 January, derived from METOSAT data for the three regions A, B and C shown in Fig. 1, were −8 °C in region A, −11 and −6 °C (bimodal) in region B, and −9 °C in region C. These values support both the pilot report and the rawinsonde-inferred cloud top of −8 or −9 °C over Bet Dagan at this time.

Cloud tops continued to lower and warm gradually, as did cloud bases during the evening and night. By 23 GMT 19 January (Fig. 6(c)) the base of the isothermal, cloud-capping layer had lowered to 800 mb and cloud tops were −5 °C.

In spite of the relatively warm cloud tops observed between 11 and 23 GMT on the 19 January, occasional very light rain continued to be observed at a number of stations from the coast to the hill region in central and northern Israel (Fig. 8). The last report of rain from this storm was at Jerusalem Airport at 00 GMT 20 January (Fig. 8(f)).

Winds at 850 and 700 mb at 11 GMT 19 January were west-north-west at 12 and 14 m s^{-1}, respectively, and 8 and 18 m s^{-1}, respectively, at 23 GMT 19 January. Thus, precipitation falling upwind of Jerusalem on the coast and at the coastal plain reporting stations could not have been the result of seeding (see section 2).

This case study shows not only that precipitation-forming processes are active in Israel when cloud top temperatures are $\geqslant -10$ °C, but also when the cloud base temperature is well below the norm of 5–8 °C and cloud depth is quite limited. In fact, the clouds on this day behaved like those that occur in the Puget Sound of Washington State (Hobbs and Rangno 1985). Maximum ice particle concentrations in modified maritime cumulus clouds in the Puget Sound routinely exceeded 10 per litre when cloud top temperatures were $\geqslant -10$ °C and they had droplet concentrations >300 cm^{-3}; the latter concentrations are comparable to those found in the cumulus clouds of Israel (e.g. Gagin and Neumann 1974).

(c) *24–25 February 1986*

A rapidly moving short wave trough embedded in a zonal current crossed Israel during the day on 24 February 1986. Isolated cumulonimbus clouds moved onshore at about 10 GMT when the axis of the trough passed overhead. Thunder was heard at Bet Dagan. These clouds moved eastward into Jordan during the afternoon and cloud cover and cloud top heights decreased noticeably over central and northern Israel as the remaining clouds diminished to cumulus mediocris and cumulus congestus.

Renewed areas of light showers began along the coast near sunset (about 15 GMT) on 24 February from clusters of modest cumulus and stratocumulus clouds that formed offshore. These scattered light showers continued to move onshore across central and northern Israel through 09 GMT 25 February (Figs. 9(a) to (f)). Figure 10 is a photograph showing a cross-section of a typical cluster of these capped cumulus congestus and stratocumulus cumulogenitus clouds south-west of Tel Aviv at daybreak (0445 GMT) on 25 February.

The rawinsonde sounding sequence for 11 GMT 24 February through 11 GMT 25 February is shown in Fig. 11. The 11 GMT 24 February sounding (Fig. 11(a)) shows the potential for deep convection in a relatively dry environment, while the 23 GMT sounding (Fig. 11(b)) illustrates the familiar pattern of a compressed region of instability and moisture in the lower layers due to subsidence following the passage of an upper

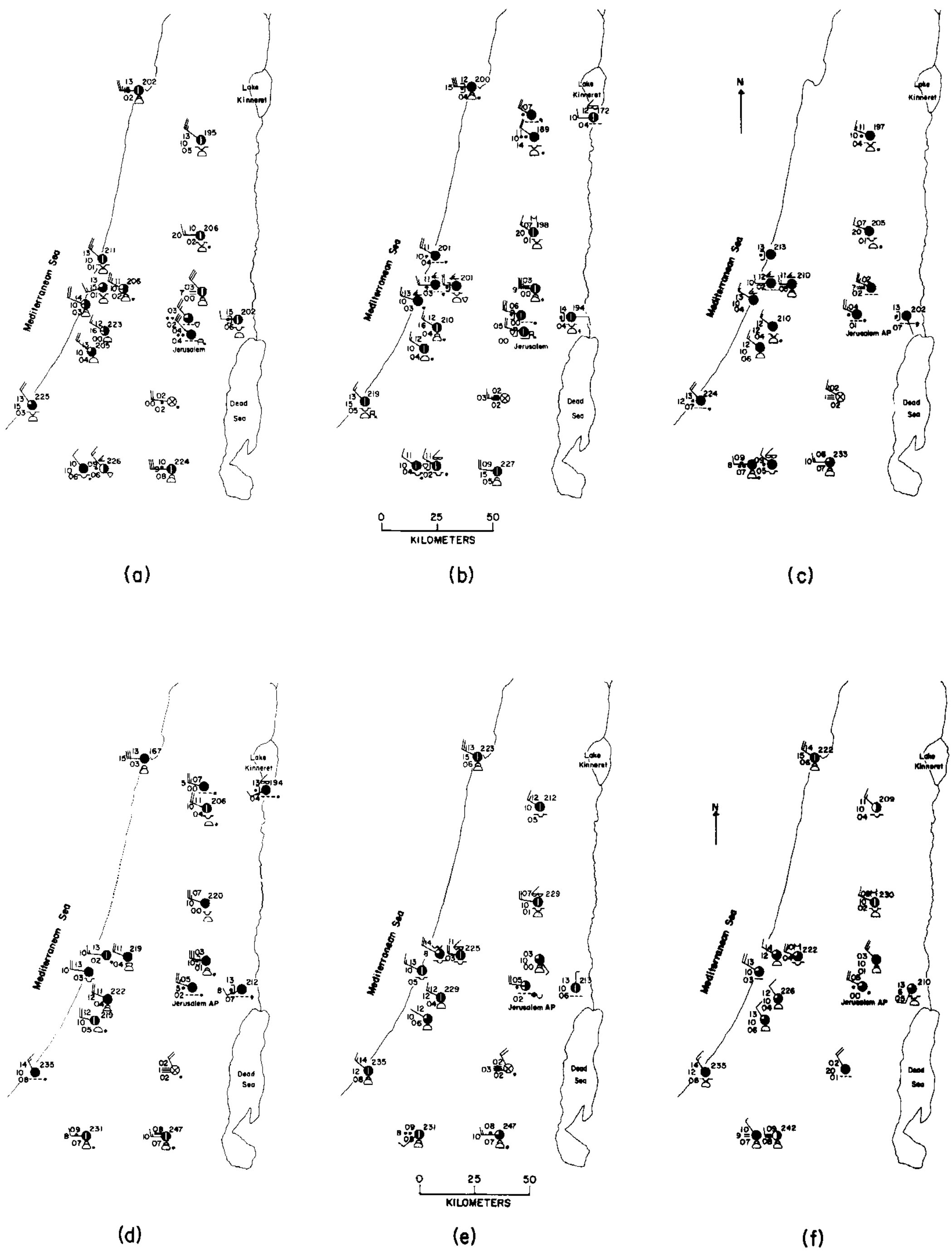

Figure 8. Surface maps for 18 January 1986 at (a) 09 GMT; (b) 12 GMT; (c) 15 GMT; (d) 18 GMT; and (e) 21 GMT; and (f) at 00 GMT on 19 January.

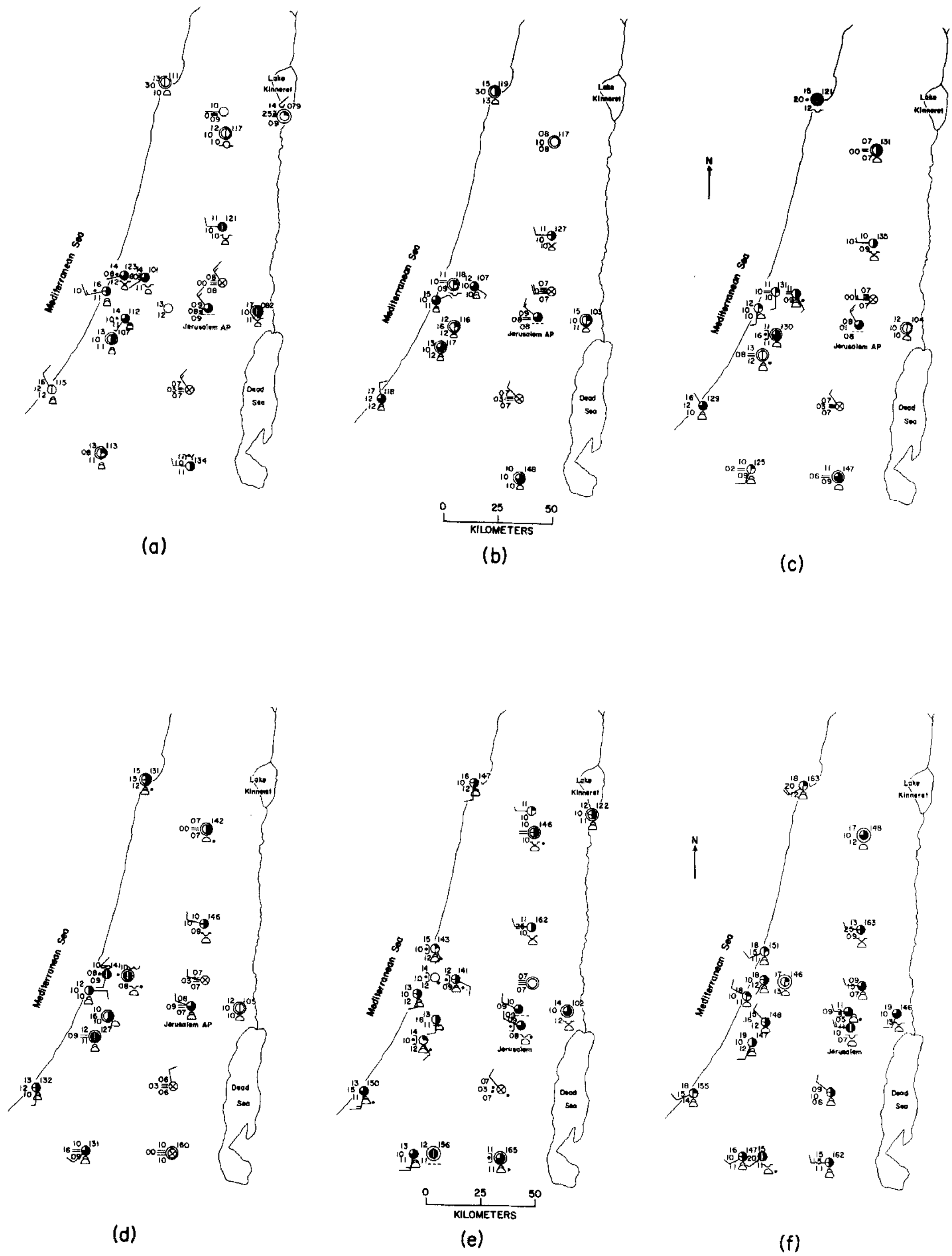

Figure 9. Surface maps for 24 February 1986 at (a) 18 GMT; (b) 21 GMT; and 25 February at (c) 00 GMT; (d) 03 GMT; (e) 06 GMT; and (f) 09 GMT.

Figure 10. Photograph taken at 0445 GMT 25 February 1986 showing cumulus congestus and stratocumulus cumulogenitus complex similar to those that produced light rain showers inland at this time. View is looking south-west from Tel Aviv.

trough. A nearly isothermal layer from 770 to 820 mb (0·5 km thick) is present on the latter sounding.

Figure 11(c) shows that the 11 GMT 25 February sounding is virtually identical to the 23 GMT 24 February sounding, indicating little change in the height of the capping stable layer between these two times. Both of these soundings indicate that the temperatures at the tops of the lightly precipitating clouds during the late evening of 24 February through the mid-morning of 25 February were between about 0 and 2 °C. Cloud bases were about 11 °C, somewhat warmer than normal.

METEOSAT-derived cloud top temperatures are not available for this case.

This storm suggests that rain can form in this region by the collision–coalescence process, which implies the presence of relatively large cloud droplets in clouds having depths of 2 km or less.

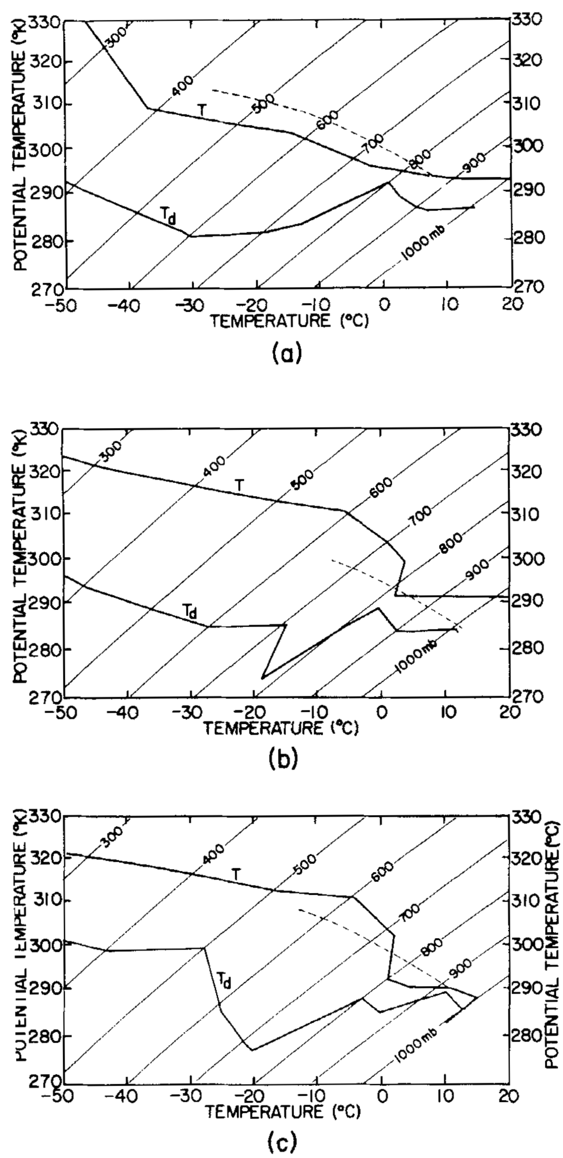

Figure 11. Rawinsonde soundings for 24 February 1986 at (a) 11 GMT; and (b) 23 GMT; and (c) at 11 GMT 25 February.

5. Discussion

Gagin and Neumann (1981) concluded that clouds over Israel precipitate inefficiently if their cloud top temperatures are $\geqslant -21\,°C$. They explained this in terms of the clouds being 'continental' in nature, that is, having relatively high ($>400\,cm^{-3}$) total concentrations of cloud droplets and negligible concentrations of large ($\geqslant 25\,\mu m$ diameter) droplets (Gagin 1971, 1975; Gagin and Neumann 1974, 1981).

Such 'continentality' in cloud microstructure would both inhibit the formation of rain by the collision–coalescence process and the production of high concentrations of ice particles by ice multiplication processes since each of these processes requires the presence of large cloud droplets (for criteria for ice multiplication see Hallett and Mossop (1974), Mossop and Hallett (1974), Mossop (1978, 1985), Gagin and Nozyce (1984), Mossop (1985), Hobbs and Rangno (1985), Rangno and Hobbs (1988)).

In this paper, we have presented evidence that it is not uncommon for clouds in Israel to precipitate when their top temperatures are $\geqslant -10$ °C. Such precipitation must form either by the collision–coalescence process or by the ice crystal mechanism (Mason 1971). The formation of rain by collision–coalescence requires droplets with diameters greater than about >40 μm (e.g. Mason 1971). Also, clouds containing such droplets should exhibit ice multiplication and therefore contain high concentrations of ice particles if their top temperatures are < -5 °C (Hobbs and Rangno 1985).

Corroborating evidence that large cloud droplets are present in the clouds over Israel is provided by the occurrence of drizzle in the hilly regions. At Jerusalem, elevation 0·7 km a.s.l., drizzle[1] accounted for 42% of the observations of precipitation at 00 or 12 GMT during the five seasons of 1955–56 through 1959–60[2]. Warm rain occurrences (see section 4, case study (c)) are further evidence that large droplets are present in these clouds before their tops reach -10 °C.

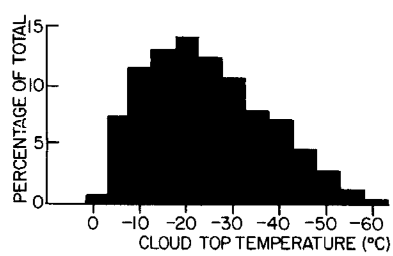

Figure 12. Summary of radar-derived cloud top temperatures for precipitating clouds collected by the Israel Meteorological Service from a site near Tel Aviv (after Gagin and Neumann 1974).

Additional evidence that clouds with top temperatures $\geqslant -10$ °C can precipitate in this region was given by Gagin and Neumann (1974). They presented data from an IMS 3 cm radar located near Tel Aviv. It can be seen from Fig. 12 that about 15% of the precipitating clouds had top temperatures $\geqslant -10$ °C, compared with 20% deduced from thirty months of rawinsonde data discussed in section 3.

6. Conclusions

The information presented in this paper indicates that it is not unusual for rain in Israel to fall from clouds with tops $\geqslant -10$ °C and at times from clouds with tops near 0 °C. This, in turn, implies that large cloud droplets and/or concentrations of ice particles are present in these clouds.

The findings in this paper differ from previous reports on cloud microstructure in Israel (Gagin and Neumann 1974, 1981; Gagin 1975). Also, Rangno and Hobbs (1988)

[1] Drizzle is defined by the World Meteorological Organisation (1969) as 'fairly uniform precipitation composed exclusively of fine drops of water (diameter <0·5 mm) very close to one another'. The author observed this type of rain in Jersualem during portions of all six appreciable storms that occurred there during January and February 1986.

[2] By the late 1970s, however, such precipitation was reported as 'one dot' rain, indicating, in the IMS nomenclature, 'very light' rain, while the 'comma' in the synoptic code, previously used by the IMS to denote drizzle, is now used to denote a 'sprinkle', that is, a fall of sparse, larger drops.

have pointed out that Gagin's (1975) report of a cloud top temperature of −17 °C for ice particle concentrations of ≈1 per litre is much colder than that suggested by a large body of worldwide airborne data for the onset of ice particles in cumulus clouds.

If precipitation routinely falls from clouds over Israel when cloud top temperatures are ⩾−10 °C, and even if these clouds contain only modest ice particle concentrations (say, 1–10 per litre), far higher ice particle concentrations (tens to hundreds per litre) would be expected in clouds with cloud top temperatures from −15 to −21 °C. If this is in fact the case, it would be difficult to explain Gagin and Neumann's (1981) report that seeding produces >40% increases in rainfall for clouds with top temperatures between −15 and −21 °C.

In view of these uncertainties in the microstructure of clouds over Israel, and their relevance to the credibility of the cloud seeding experiments conducted there, extensive independent airborne measurements are needed in this region, as recommended by Hobbs (1982).

ACKNOWLEDGMENTS

The author is greatly indebted to the Israel Meteorological Service (IMS) and in particular to Y. L. Tokatly, Director, for allowing access to the IMS archives from which the surface observations and rawinsonde data originate. Particular assistance with the IMS archive data was given by Sara Rubin and Ronit Ben-Sarah. Dr J. O. Rhea also contributed several helpful comments. Dr P. Jonas of the British Meteorological Office kindly provided the METEOSAT data. Finally, and most importantly, I owe a profound debt to Professor Peter V. Hobbs for his counsel and careful guidance and advice in the writing of this paper.

REFERENCES

Gagin, A. 1971 'Studies of the factors governing the colloidal stability of continental cumulus clouds'. Pp. 5–11 in 'Preprints international conf. on weather modification. Canberra'. American Meteorological Society

1975 The ice phase in winter continental cumulus clouds. *J. Atmos. Sci.*, **32**, 1604–1614

Gagin, A. and Neumann, J. 1974 'Rain stimulation and cloud physics in Israel'. Pp. 454–494 in *Climate and weather modification*. Ed. W. N. Hess. Wiley and Sons, New York

1981 The second Israeli randomized cloud seeding experiment: evaluation of results. *J. Appl. Meteorol.*, **20**, 1301–1311

Gagin, A and Nozyce, H. 1984 The nucleation of ice crystals during the freezing of large supercooled drops. *J. Rech. Atmos.*, **18**, 119–129

Hallett, J. and Mossop, S. C. 1974 Production of secondary ice particles during the riming process. *Nature*, **249**, 26–28

Hill, G. E. 1982 'Evaluation of the Utah operational weather modification program'. Pp. 138–143 in Final report, Utah State University Water Resources Laboratory, Logan, Utah

Hobbs, P. V. 1982 Cloud seeding. *Science*, **218**, 426

Hobbs, P. V. and Rangno, A. L. 1985 Ice particle concentrations in clouds. *J. Atmos. Sci.*, **42**, 2523–2549

Mason, B. J. 1971 *The physics of clouds.* Oxford University Press, Glasgow

Mossop, S. C. 1978 The influence of the drop size distribution on the production of secondary ice particles during graupel growth. *Q. J. R. Meteorol. Soc.*, **104**, 323–330

1985 Microphysical properties of supercooled cumulus clouds in which an ice particle multiplication process operated. *ibid.*, **111**, 183–198

Mossop, S. C. and Hallett, J.	1974	Ice crystal concentration in cumulus clouds: influence of the drop spectrum. *Science*, **186**, 632–634
Mossop, S. C. and Ono, A.	1969	Measurements of ice crystal concentrations in clouds. *J. Atmos. Sci.*, **26**, 130–137
Rangno, A. L. and Hobbs, P. V.	1988	Criteria for the onset of significant concentrations of ice particles in cumulus clouds. *Atmos. Res.*, **22** (in press)
World Meteorological Organisation	1969	*International cloud atlas*: *Abridged atlas*. Geneva