NOTES AND CORRESPONDENCE

Winter Thunderstorms in Israel: A Study with Lightning Location Systems and Weather Radar

ORIT ALTARATZ AND ZEV LEVIN

Department of Geophysics and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

YOAV YAIR

Department of Natural and Life Sciences, The Open University of Israel, Tel Aviv, Israel

24 June 2000 and 4 October 2000

ABSTRACT

A study of the morphology and evolution of winter thunderstorms in Israel and over the eastern Mediterranean was conducted during the 1995–96 winter season. Electrically active cells were analyzed by combining data from weather radar and an operational lightning positioning and tracking system. This enabled the identification of reflectivity features of electrically active cells, and tracing of the spatial and temporal evolution of thunderstorms. The results show that, in winter, rain clouds became thunderclouds if their echo top was higher than 6500 m (at a temperature level colder than −30°C), provided that the reflectivity at the level of the −10°C isotherm was larger than 35 dB*Z*. The period between the first radar echo and the first detected lightning flash (probably a ground flash) was found to be 10–15 min, a period at which the top of the 40-dB*Z* echo was located higher than the −8°C level.

1. Introduction

Global observations of lightning activity from spaceborne platforms (Orville 1981; Christian et al. 1999) show that in Northern Hemisphere winter, lightning frequency over mainland Europe and Asia is extremely low. However, the eastern Mediterranean region exhibits a marked and sustained lightning activity during the winter months (Dec–Jan–Feb, DJF). While the majority of thunderstorms seem to occur over the relatively warm seawater, some thunderstorms cross over to land. This pattern resembles the lightning activity observed over the Sea of Japan, which is also a significant lightning generating region in winter. For a vivid, albeit qualitative, impression of the relative contributions of these two regions to the global lightning budget we refer the reader to the monthly averages obtained from optical transient detector measurements in the past five years, published on the Internet (Christian et al. 1999; http://thunder.msfc.nasa.gov/).

Although numerous studies were conducted on summer thunderstorms, relatively far fewer were published on winter thunderstorms. Following is a brief review of the main findings on the two categories.

a. Summer and tropical thunderstorms

Several threshold values for the occurrence of electrical activity in summer thunderstorms have been determined in previous studies. Larsen and Stansbury (1974) found that the 43-dB*Z* echo had to rise above the level of the −30°C isotherm (at the height of 7000 m) for electrical activity to commence in thunderstorm in Montreal, Canada. Dye et al. (1989) studied thunderstorms in New Mexico and found that a strong electric field (>1000 V m^{-1}) appeared simultaneously with the ascending of the 40-dB*Z* echo to the height of the −10°C isotherm. Zipser and Lutz (1994) found that most thunderclouds in midlatitudes are well within Dye et al.'s criterion. Petersen et al. (1996) studied tropical oceanic storms and determined a reflectivity threshold for lightning generation of 30 dB*Z* above the −10°C isotherm height. The growth in the height of the strong echoes within the clouds could be interpreted as reflecting the increasing depth in which large precipitation formed (including graupel particles) during strong convection.

Corresponding author address: Prof. Zev Levin, Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv 69978, Israel.
E-mail: zev@hail.tau.ac.il.

Some studies tried to determine how lightning activity evolves during the different stages of the life cycle of the storm. Poehler (1978) showed that the peak ground flash rate appeared 8–10 min after the maximum cloud-top height has been reached. Atchley (1983) found that the maximum rain intensity at ground level appeared 5 min after the peak flash rate. Lhermitte and Williams (1984) found a correlation in time between the electrical activity and the vertical development of the cell. The core of the high reflectivity was lowered to ground level 8–10 min after the maximum in electrical activity, indicating heavy precipitation and dissipation of the cloud.

b. *Winter thunderstorms*

The relative rarity of midlatitudes winter thunderstorms (as compared to the prevalent tropical and midlatitude summertime storms) makes them an interesting target for study. In the coastal area of Japan, Tomine et al. (1986) and later Michimito (1991) found that the temperature of $-20°C$ at the level of cloud top was a threshold value for a cloud to become a thundercloud. Michimito also found that the $-10°C$ isotherm had to be higher than 1.4 km in those storms and the 30-dBZ echo had to be above the $-20°C$ level (indicating strong enough updrafts to produce electrification). A study by Takahashi (1996) of 19 winter thunderstorms in the Hokuriku district, involving Doppler radar and videosonde observations, showed the importance of ice crystal–graupel interactions in cloud electrification. Recently, Shimura et al. (1999) and Kami et al. (1999) reported the results of studies conducted in western Japan on the relationship between radar echoes, the appearance of graupel particles, and lightning frequency in winter thunderclouds.

c. *Winter thunderstorms in the eastern Mediterranean*

Levin et al. (1996) and Yair et al. (1998) have reviewed the meteorological conditions for thunderstorm development in Israel in detail. Most thunderstorms in the eastern Mediterranean occur in the winter season between December and February, and to a much lesser extent in the spring (Mar–May) and autumn (Oct–Nov). These thunderstorms are usually associated with the passage of ''Cyprus lows,'' cyclones that originate in southern Europe and travel over the northern part of the eastern Mediterranean Sea. The air masses in Israel in these situations originate from Europe and are modified by the influence of the warmer water of the Mediterranean Sea. This modification results in an increase in moisture and in static instability, due to the sensible heat flux from the sea surface (Alpert and Reisin 1986). Almost all thunderclouds develop at the cold front or just immediately after its passage, within the cold air mass. This type of storm is very similar to winter thunderstorms in western Japan (Michimoto 1991, 1993), and is different from the continental, summertime mesoscale convective system type thunderclouds, which are prevalent in the United States. The meteorological resemblance of these conditions to those found in western Japan have been discussed by Yair et al. (1998) and Altaratz et al. (1999).

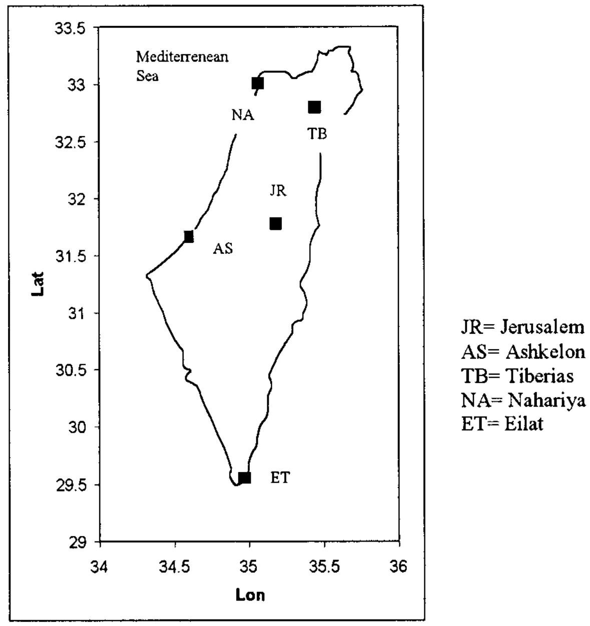

FIG. 1. Map of Israel with the locations of the LPATS receivers.

A different, less prevalent, synoptic situation for the occurrence of thunderstorms is the Red Sea Trough, a tropical low pressure wave from the Red Sea that intrudes toward the Mediterranean Sea. Israel is then influenced by warm, relatively dry and unstable air masses at low levels, accompanied by a southerly moist upper-level airflow (Dayan and Sharon 1980; Levin et al. 1996).

The present report focuses on the characteristics of winter thunderstorms in the eastern Mediterranean, as derived from single-cell analysis using weather radar and lightning positioning system. This method is widely used in various studies of summer and winter storms alike, which strive to correlate the evolution of radar echoes with the electrical activity of thunderstorms (Michimoto 1991; Rutledge and Peterson 1994; Zipser and Lutz 1994; Kitagawa and Michimoto 1994).

2. Instrumentation and analysis method

Observations of lightning, which included the time, location, type, and peak currents of strokes, were obtained from the lightning positioning and tracking system (LPATS) operated by the Israeli Electrical Company. During the study period, the system was based on five measuring stations and a central processing unit located near Mount Carmel in Haifa. The stations are located in Eilat, Ashkelon, Tyberias, Nahariya, and Jerusalem (Fig. 1), ensuring an average range of 500 km from the center of Israel. The detection efficiency of the system depends on the location of the storm relatively to the network, but the overall efficiency is estimated to be 70%–90% for ground flashes and less than 10% for cloud flashes (Finke and Hauf 1996; Pinto et al. 1996). Recently it was modified to include Improved Accuracy from Combined Technology (IMPACT) sensors that will improve its performance. Although reference will be made to numbers of cloud flashes, these probably represent only a low percentage of the actual number of cloud flashes occurring in our region.

Precipitation observations were carried out with a C-band WR-100-5 weather radar (wavelength 5.6 cm) located at Tel Aviv University (TAU). The rotation rate is 3 min^{-1}, and maximum power is 2500 W. The pulse repetition frequency is 250 Hz and the beamwidth is 1.5°. A complete volume scan takes 5 min and is composed of 12 elevation angles, from 0.5° to 20°. In order to obtain good resolution reflectivity measurements, we only analyzed clouds within a range of 60 km from the radar.

The meteorological and synoptic conditions for each thunderstorm event were obtained from radiosondes released by the Bet-Dagan meteorological station (twice a day at 0000 and 1200 UTC), which is located 8 km southeast of Tel Aviv, and from synoptic maps.

The method of data analysis was based on the following procedure: (a) identifying the convective cells within the radar's constant-altitude plan position indicator (CAPPI) image at 2700 m, (b) performing horizontal and vertical cross sections of the digitized radar echoes, (c) analyzing the cell's characteristics (reflectivity, cloud-top height, rain intensity) during its life cycle, and (d) ascribing lightning strikes to the cell. Flashes were considered to be produced by a specific thundercloud if their ground contact points were located within a distance of less than 10 km from the central echo (MacGorman et al. 1989). The precipitation intensity was calculated according to the Z–R relation: $Z = 330R^{1.4}$ (Feingold and Levin 1986), using Z at the base scan level (below 1 km) to an accuracy of ±5 dBZ.

3. Results and discussion

The number of events for which we had a good radar coverage (cell range not exceeding 60 km from TAU radar) and concurrent lightning position data was rather limited. A total of 14 electrically active cells, from four different lightning days, were analyzed using this method (the results are presented in Table 1). In some of the cases the analysis was done for two or three cells evolving together in the same area, due of the difficulty of separating them in the radar image (they are marked in the table in the flash rate column). In those cases the values presented are those of the stronger cell.

We present the detailed analysis of two cells, as representative examples of the method of analysis. The first cell is a part of the storm of 24 March 1996. This storm generated lightning during the afternoon, for several hours, over the sea and over the land. The surface pressures map in Fig. 2 from 0200 local time (LT; 0000 UTC) 25 March 1996 shows a barometric low located in the Bay of Alexandreta in southern Turkey. At the upper levels, a low centered over the southern part of Turkey caused cold continental European air to stream southward. The freezing level in this event was located at 1600 m. Figure 3a shows the radar CAPPI image at 2700 m at 1901 LT, with the superimposed locations of the detected lightning flashes. Positive ground flashes (PGFs) are marked by a plus sign (+), negative ground flashes (NGFs) by an asterisk (*), and cloud flashes (CFs) by an open circle (○). We followed the cell (marked by A7) for 30 min, as it moved over the land with southwest winds. We detected 41 flashes during 35 min, consisting of 26 cloud flashes, 12 negative ground flashes, and 3 positive ground flashes. It is quite probable that in reality the cloud flash rate was much higher, but due to the low detection efficiency of the LPATS many CFs were missed. Figure 3b shows four vertical cross sections of the cell in different stages of its life cycle. In the first profile (1852 LT) the cell was in the developing stage. The strongest echoes were found in the middle part of the cell (45 dBZ at 3 km), and it did not produce any flashes during that time. The cloud continued to develop and at 1856 LT the maximum reflectivity reached 45 dBZ at the height of 3.3 km. At 1901 LT it was 50 dBZ at 3.8 km. During the time interval between 1856 and 1900 LT the cell produced 14 flashes, and between 1901–1905 LT an additional 12 flashes were recorded. The maximum lightning activity appeared during the mature stage of the cell. At this stage high reflectivity values (45–50 dBZ) were found at temperatures lower than −10°C. These reflectivity values are indicative of the presence of graupel particles within this layer in the cloud (Ziegler et al. 1986; Michimoto 1991). Figure 4 presents the change in time of two cell parameters: the maximum radar reflectivity (in time intervals of 5 min), and the flashes that it produced (recorded continuously in time). It is clearly evident that the peak in the flash rate was correlated in time with the maximum radar reflectivity of the cell. During the period between 1852 and 1906 LT the maximum reflectivity (45–50 dBZ) was located in temperatures levels between −10° and −20°C, in the mixed phase part of the cloud where the charge separation processes take place. By looking again in the vertical cross sections we can see that these maxima occurred during the mature stage in the life cycle of the cloud. For the summarized characteristics of cell A(7), see Table 1.

The second storm occurred on 3 January 1996. This typical winter storm was associated with a cold front that advanced toward the Israeli shoreline in the evening hours, steered by the prevailing southwesterly winds. The surface map for 0200 LT (0000 UTC) 4 January 1996 is presented in Fig. 5. At the surface level, the low's center was located between Cyprus and Crete, and

TABLE 1. Summary of radar reflectivity and lightning occurrence of the active cells. 1) For the cases where the cells were too close to the radar (less than 20 km) there are no measurements of heights. 2) For two cells [A(3) and A(17)] the temperatures that were measured for the 30- and 40-dBZ echo heights, at the time of the first flash, were unusually high and they are marked by asterisks.

Cell	Max height (km)	Max ref. (dBZ)	Max rain intensity (mm h^{-1})	Max ref. at the −10°C level (dBZ)	Max flash rate [no. (5 min)$^{-1}$]	Time between max ref. and max flash rate (min)	Time between first echo and first flash (min)	Temp level of 40-dBZ echo during the first flash (°C)	Temp level of 30-dBZ echo during the first flash (°C)	Ref. at the −10°C level in the time of the first flash (dBZ)
11 Dec 1995										
A(1)	8	52	82	47	11 (two cells)	—	10	−13	−22	42
A(2)	9	47	36	47	5	0	—	−13	−22	42
A(3)	9.5	52	82	47	22 (two cells)	—	—	*−1	*−10	32
24 Mar 1996										
A(6)	6.5	45	26	35	2	0	10	−8	−24	35
A(7)	7	50	59	50	14	0	10	−15	−25	45
A(8)	6.5	45	26	45	8	0	15	−13	−22	45
3 Jan 1996										
A(9)	9	50	26	45	17	0	10	−9	−16	40
A(10)	—	60	134	60	15	—	10	−22	−25	45
A(11)	—	60	134	55	11	0	—	—	—	—
A(12)	—	55	134	55	7	0	—	—	—	—
5 Nov 1996										
A(13)	10.5	55	134	50	7 (two cells)	—	10	−27	−27	50
A(16)	9.5	50	26	45	6	—	—	—	−12	35
A(17)	8.5	50	59	45	4	0	—	—	*−3	40
A(19)	13	45	26	50	17 (three cells)	—	—	—	−19	40

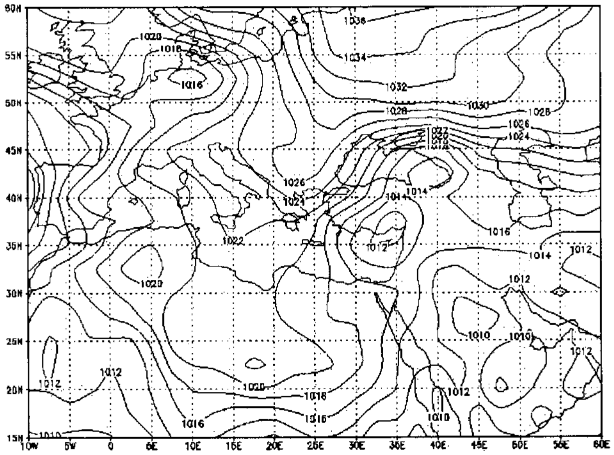

FIG. 2. Surface pressure map for 0200 LT (00 UTC) 25 Mar 1996.

a cold front had already moved eastward across Israel. In the upper levels there was a large trough that intruded from northern Europe into the Mediterranean, and caused cold flow to the region. The freezing level was found at 2100 m above mean sea level (MSL). The radar CAPPI image at 2700 m from 1840 LT (Fig. 3c) is superimposed with the location of the detected lightning strikes marked on it (PGF are marked by plus signs, NGF by asterisks, and CF by open circles). The cell [marked as A(9)] was monitored for 49 min, as it moved over the sea, until it reached a point 40 km north of Tel Aviv. We detected 46 flashes during 30 min: 26 CF, 16 NGF, and 4 PGF. Figure 6 presents the evolution of the heights of the 40-, 30-, and 20-dB*Z* echoes, together with the detected flashes generated by the thundercloud (in 5-min intervals). The 20-dB*Z* echo reached its maximum height only after the time of the maximum flash rate (between 1840 and 1844 LT the cloud generated 17 flashes), indicating that the cloud was still developing vertically during the lightning activity. The first flash was detected 10 min after the first radar echo of the cell (10-dB*Z* echo), as the top of the 40-dB*Z* echo reached 3500 m (the level of the $-9°$C isotherm). At that time the top of the 30-dB*Z* echo had reached the $-16°$C level (4500 m).

The findings of the present study enable us to preliminarily characterize winter thunderstorms in the eastern Mediterranean region. We can also consider these values as threshold values, which can help determine whether a convective cell evolving in a wintertime low pressure system in this region would become a thundercloud. The first characteristic is that the echo top of the thundercloud is higher than 6500 m. This height is higher than the 5-km top height that Brook et al. (1982) measured for the winter thunderclouds in Japan. The echo tops of the eastern Mediterranean thunderclouds are at temperature levels colder than $-30°$C, lower than the $-20°$C value that Michimoto (1991) found for winter's thunderstorms in Japan. Possible reasons for these differences will be discussed later in this section.

Another characteristic of thunderclouds in the eastern Mediterranean region is that the reflectivity at the $-10°$C level is greater than 35 dB*Z*. In fact, 13 out of the 14 analyzed cells (see Table 1) were above the criterion of 40 dB*Z* at the $-10°$C level suggested by Dye et al. (1989). The last general feature is that radar-derived rain intensity of the cell is higher than 26 mm h^{-1}.

In an analogous manner, the parameters that define the onset of ground flashes can be determined. We found that the period between the first radar echo (10 dB*Z*) and the first ground flash is 10–15 min. Fujita and Black (1988) and Lhermitte and Williams (1984) reported similar findings. Mason (1971) summarized the observed features of thunderstorms and he determined that sufficient charge must be separated to supply the first lightning flash within 12–20 min of the appearance of particles of radar detectable size ($D > 0.2$ mm). Using a one-dimensional model (which accounted only for the noninductive charge separation mechanism) Ziegler et al. (1986) calculated a time difference of 12 min between the appearance of the 10-dB*Z* echo in the model and the build up of a 300 kV m^{-1} electric field (which is sufficient for lightning initiation). A different model, which was used by Norville et al. (1991) and was based on the same charge separation mechanism, gave 15 min for this time difference. It is clear therefore that the present measurements are in good agreement with the model calculations and with the observed values.

The heights of different reflectivity values at the time of the first flash can be determined. The tops of the 40-dB*Z* echo are located at temperature levels colder than $-8°$C and the tops of the 30-dB*Z* echo are higher than the $-12°$C level. For two cells [marked by A(3) and A(17)] the temperatures that were measured for the 30- and 40-dB*Z* echoes height, at the time of the first flash, were unusually high (they are marked by asterisks in Table 1). The reason for these relatively warmer temperatures is not entirely clear. However, it is possible that due to the low detection rate of intracloud flashes by the LPATS, the detected flashes actually occurred during the dissipating stage of the cloud, as the precipitation cores were descending, and not during the mature stage. Because of the uncertainty in these two cases, they were not included in the final analysis.

Based on the common features of the analyzed winter thunderstorms, it seems that the onset of lightning activity appears during the beginning of the mature stage of cloud development. The maximum of the lightning frequency appears at the end of the mature stage. In this stage the cells develop upward and the radar echoes intensify while moving to higher altitudes. At the same time large precipitation particles fall (outside the main core of the updraft) and reach the ground. The duration of this stage is about 15 min (Rogers and Yau 1989). The first ground flash usually occurs 10–15 min after the first radar echo appears. The peak of the electrical activity is well correlated in time with the maximum radar reflectivity at the $-10°$C level. The high reflec-

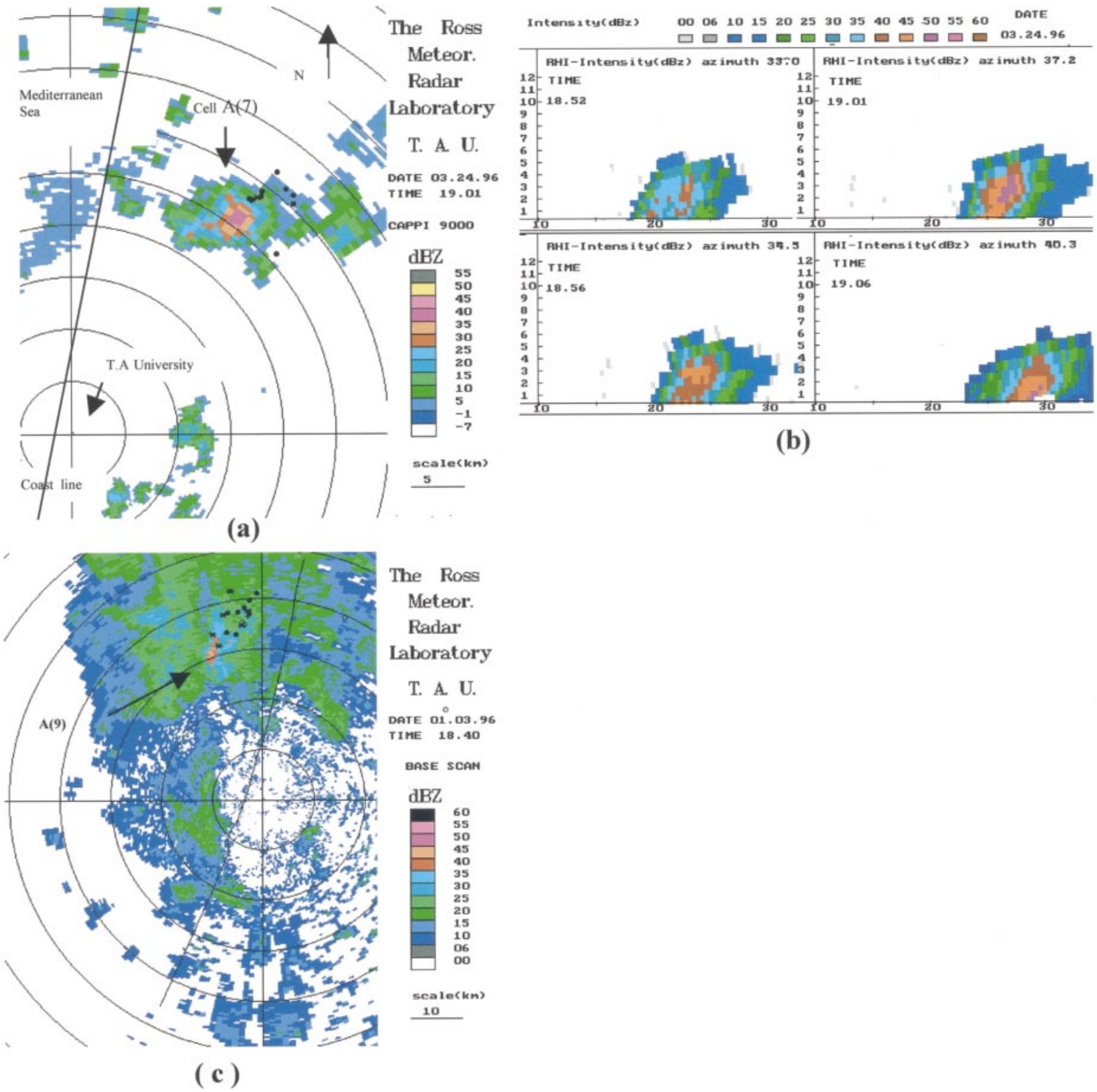

FIG. 3. (a) Radar CAPPI image at 2700 m at 1901 LT (1701 UTC 3 Mar 1996). (b) Vertical profiles of the cell [marked by (A7)] between 1852 and 1906 LT (height and distance from the radar are given in km). (c) Radar CAPPI image at 2700 m at 1840 LT (1640 UTC 3 Jan 1996).

tivity at this level indicates the presence of large precipitation particles that are carried up by the strong updrafts. A notable feature was the appearance of echoes stronger than 35–40 dB*Z* at levels higher than the −10°C level, probably indicating the appearance of graupel particles, a major component in the graupel–ice particles noninductive mechanism (Williams et al. 1994). All of these ensure a high number of particle interactions and an efficient charge separation process (Takahashi 1984). Results of a numerical axisymmetric model that treated the water and ice microphysical processes in continental clouds in detail can give us some idea about the quantitative characteristics of these clouds (Reisin et al. 1996). Using initial conditions that resembled the Israeli winter conditions resulted in a cloud base at 1200 m (at the level of 5°C) and a cloud tops at 4800 m. The maximum updraft was 14 m s^{-1} and the maximum water liquid content was 3.8 g kg^{-1}.

The present study points to further similarities between winter thunderclouds in the eastern Mediterranean and in western Japan. In events that are associated with the passage of cyclonic lows, the synoptic conditions in both areas in winter are similar. Cold, dry, continental air masses originating in Europe (continental

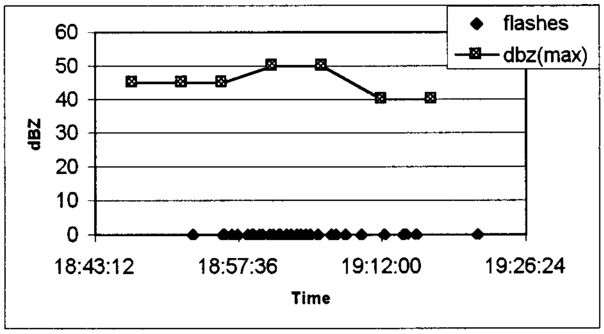

FIG. 4. Evolution of the cell's maximum reflectivity and the timing of the flashes that were produced by this cell [marked by (A7)].

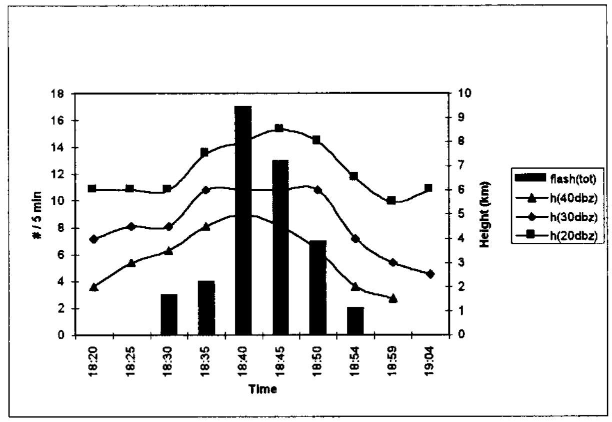

FIG. 6. Evolution of the 40-, 30-, and 20-dBZ echo heights and the total flash count of cell A(9).

China) are passing over relatively warm Mediterranean (Sea of Japan) water, changing, and becoming unstable as they approach the coast. They generate convective clouds and thunderstorms. Michimoto (1991) studied the microphysical properties of these thunderclouds and showed that the necessary conditions for the development of lightning activity in Japan are 1) a fast vertical movement of the 40–50-dBZ echoes, and 2) cloud tops at temperatures colder than -20°C. Similarly, thunderclouds in the Mediterranean also exhibit a reflectivity threshold of 45 dBZ. However, in contrast to Japan, Mediterranean clouds need to reach temperatures lower than -30°C that reside at higher altitudes above MSL. This difference probably arises from the fact that Japan, beside being at more northern latitudes, experiences colder atmospheric temperatures during winter than Israel because the cold air from Siberia travels over very cold landmass before reaching the Sea of Japan. In contrast, cold air coming from Europe warms up as it passes over larger distance over the Mediterranean Sea, picking more moisture on its way toward Israel. Therefore ice crystals and graupel particles, essential for charge separation, are found at lower altitudes in the Japanese clouds. Furthermore the clouds in Japan have smaller vertical extent (Brook et al. 1982; Takahashi et al. 1999) and as a result of the colder temperatures, they precipitate snow, and not only rain, as is the case in Israel (Takahashi et al. 1999; Uyeda et al. 1996).

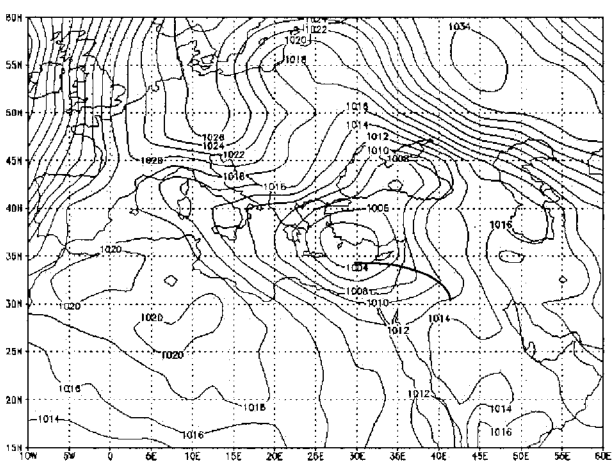

FIG. 5. Surface pressure map for 0200 LT (0000 UTC) 4 Jan 1996.

4. Summary

This study tries to better characterize winter thunderclouds in the eastern Mediterranean. The threshold parameters for lightning generation in winter thunderclouds are as follows.

1) The top of the clouds must be higher than 6.5 km (at a temperature level colder than -30°C).
2) The maximum reflectivity should be higher than 45 dBZ.
3) The intensity of the reflectivity at the -10°C level should exceed 35 dBZ.
4) The radar-derived rain intensity of the cell is higher than 26 mm h^{-1}.

Then the following parameters define the beginning of the ground lightning activity.

1) The period between the first radar echo and the first cloud to ground lightning is 10–15 min.
2) The top of the 40-dBZ echo should be higher than the -8°C level.
3) The top of the 30-dBZ echo should be higher than the -12°C level.
4) The reflectivity at the -10°C level should be more than 32 dBZ at the time of the first ground discharge.

The present study also points to further similarities between winter thunderclouds in the eastern Mediterranean and in western Japan. Although the typical cells in Japan are smaller than the ones in Israel, the parameters measured by the radar are almost the same. Further studies on the properties of winter thunderclouds in the region are needed. That will have to include remote observations and possibly in situ measurements of the ambient electric field inside and below active thunderclouds.

Acknowledgments. This research was supported by the Basic Research Foundation of the Israeli Academy of Sciences and Humanities. LPATS data were obtained courtesy of the Israeli Electrical Company. Thanks are due to the Ross family for their support of the Ross Meteorological Radar Laboratory at Tel Aviv University. NCEP reanalysis data were provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site (http://www.cdc.noaa.gov/).

REFERENCES

Alpert, P., and T. Reisin, 1986: An early winter polar air mass penetration to the eastern Mediterranean. *Mon. Wea. Rev.,* **114,** 1411–1418.

Altaratz, O., Z. Levin, and Y. Yair, 1999: Electrical and radar observation of thunderstorms in the eastern Mediterranean. Preprints, *11th ICAE Meeting,* Guntersville, AL, ICAE, 468–471.

Atchley, A. A., 1983: Case study of August 7 thunderstorm over Langmuir Laboratory. *Proceedings in Atmosphere Electricity,* L. H. Ruhnke and J. Latham, Eds., A. Deepak, 301–303.

Brook, M., M. Nakano, P. Krehbiel, and T. Takeuti, 1982: The electrical structure of the Hokuriku winter thunderstorms. *J. Geophys. Res.,* **87** (C2), 1207–1215.

Christian, H. J., and Coauthors, 1999: Global frequency and distribution of lightning as observed by the optical transient detector (OTD). Preprints, *11th ICAE Meeting,* Guntersville, AL, ICAE, 726–729.

Dayan, U., and D. Sharon, 1980: Meteorological parameters for discriminating between widespread and spotty storms in the Negev. *J. Earth. Sci.,* **29,** 253–256.

Dye, J., W. Winn, J. Jones, and D. Breed, 1989: The electrification of New Mexico thunderstorms. 1. The relationship between precipitation development and the onset of electrification. *J. Geophys. Res.,* **94** (D6), 8643–8656.

Feingold, G., and Z. Levin, 1986: The lognormal fit to raindrop spectra from frontal convective clouds in Israel. *J. Climate Appl. Meteor.,* **25,** 1346–1363.

Finke, U., and T. Hauf, 1996: The characteristics of lightning occurrence in southern Germany. *Beitr. Phys. Atmos.,* **69,** 361–374.

Fujita, T. T., and P. G. Black, 1988: Monrovia microburst of 20 July 1986: A study of ''SST.'' Preprints, *15th Conf. on Severe Local Storms,* Baltimore, MD, Amer. Meteor. Soc., 381–383.

Kami, K., K. Shinjo, T. Sakai, and T. Wakai, 1999: Lightning activities in winter thundercloud observed by dual-polarization Doppler radar on the Hokuriku coast of Japan. Preprints, *11th ICAE Meeting,* Guntersville, AL, ICAE, 452–455.

Kitagawa, N., and K. Michimoto, 1994: Meteorological and electrical aspects of winter thunderclouds. *J. Geophys. Res.,* **99** (D5), 10 713–10 721.

Larsen, H. R., and E. J. Stansbury, 1974: Association of lightning flashes with precipitation cores extending to height 7 km. *J. Atmos. Terr. Phys.,* **36,** 1547–1553.

Levin, Z., Y. Yair, and B. Ziv, 1996: Positive cloud-to-ground flashes and wind shear in Tel-Aviv thunderstorms. *Geophys. Res. Lett.,* **23,** 2231–2234.

Lhermitte, R. M., and E. R. Williams, 1984: Doppler radar and electrical activity observation of a mountain thunderstorm. Preprints, *22d Conf. on Radar Meteorology,* Zurich, Switzerland, Amer. Meteor. Soc., 83–90.

MacGorman, D. R., D. W. Burgess, V. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson, 1989: Lightning rates relative to tornadic storm evolution on 22 May 1981. *J. Atmos. Sci.,* **46,** 221–249.

Mason, B. J., 1971: *The Physics of Clouds.* Oxford University Press, 671 pp.

Michimoto, K., 1991: A study of radar echoes and their relation to lightning discharge of thunderclouds in the Hokuriku district, Part 1: Observation and analysis of thunderclouds in summer and winter. *J. Meteor. Soc. Japan,* **69,** 327–335.

——, 1993: A study of radar echoes and their relation to lightning discharge of thunderclouds in the Hokuriku district, Part 2: Observation and analysis of ''single flash'' thunderclouds in midwinter. *J. Meteor. Soc. Japan,* **71,** 195–203.

Norville, K., M. Baker, and J. Latham, 1991: A numerical study of thunderstorm electrification: Model development and case study. *J. Geophys. Res.,* **96** (D4), 7463–7481.

Orville, R. E., 1981: Global distribution of midnight lightning September to November 1977. *Mon. Wea. Rev.,* **109,** 391–395.

Petersen, W. A., S. A. Rutledge, and R. E. Orville, 1996: Cloud-to-ground lightning observation from TOGA COARE: Selected results and lightning location algorithms. *Mon. Wea. Rev.,* **124,** 602–620.

Pinto, O., Jr., R. B. B. Gin, I. R. C. A. Pinto, O. Mendes Jr., J. H. Diniz, and A. M. Carvalho, 1996: Cloud to ground lightning flash characteristics in southeastern Brazil for the 1992–1993 summer season. *J. Geophys. Res.,* **101** (D23), 29 627–29 635.

Poehler, H. A., 1978: LDAR observations of a developing thunderstorm and weather radar data including the first report of the design and capabilities of a new time of arrival ground strike locations system. NASA Contract Rep. CR-15426, 55 pp.

Reisin, T., Z. Levin, and S. Tzivion, 1996: Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. Part I: Description of the model. *J. Atmos. Sci.,* **53,** 497–519.

Rogers, R. R., and M. K. Yau, 1989: *A Short Course in Cloud Physics.* Pergamon Press, 293 pp.

Rutledge, S. A., and W. A. Peterson, 1994: Vertical radar reflectivity structure an cloud to ground lightning in the stratiform region of MCSs: Further evidence for in situ charging in the stratiform region. *Mon. Wea. Rev.,* **122,** 1760–1776.

Shimura, T., F. Kobayashi, T. Shindo, A. Wada, and T. Sakai, 1999: Characteristics of ''superbolt'' related winter thunderclouds over the Japan Sea. Preprints, *11th ICAE Meeting,* Guntersville, AL, ICAE, 380–383.

Takahashi, T., 1984: Thunderstorm electrification—A numerical study. *J. Atmos. Sci.,* **41,** 2541–2558.

——, 1996: Videosonde observation of winter thunderstorms. Preprints, *10th ICAE Meeting,* Osaka, Japan, ICAE, 552–555.

——, T. Tajiri, and Y. Sonoi, 1999: Charges on graupel and snow crystals and the electrical structure of winter thunderstorms. *J. Atmos. Sci.,* **56,** 1561–1578.

Tomine, K., K. Michimoto, and S. Abe, 1986: Studies on thunderstorm in winter in the area surrounding Komatsu by radar (in Japanese). *Tenki,* **33,** 445–452.

Uyeda, H., T. Otsu, H. Kagaya, Y. Asuma, K. Kikuchi, Z. Kawasaki, and Y. Sonoi, 1996: Characteristics of winter thunder clouds observed by a dual-polarization doppler radar around Wakasa Bay, west coast of Japan. Preprints, *10th ICAE Meeting,* Osaka, Japan, ICAE, 568–571.

Williams, E. R., R. Zhang, and D. Boccippio, 1994: Microphysical growth state of ice particles and large-scale electrical structure of clouds. *J. Geophys. Res.,* **99** (D5), 10 787–10 792.

Yair, Y., Z. Levin, and O. Altaratz, 1998: Lightning phenomenology in the Tel Aviv area from 1989 to 1996. *J. Geophys. Res.,* **103,** 9015–9025.

Ziegler, C. L., P. S. Ray, and D. R. MacGorman, 1986: Relations of kinematics, microphysics and electrification in an isolated mountain thunderstorm. *J. Atmos. Sci.,* **43,** 2098–2114.

Zipser, E. J., and K. Lutz, 1994: The vertical profile of radar reflectivity of convective cells: A strong indicator of storm intensity and lightning probability? *Mon. Wea. Rev.,* **122,** 1751–1759.