Lightning Activity over Land and Sea on the Eastern Coast of the Mediterranean

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ABSTRACT

This paper presents a study of the characteristics of lightning activity during the Cyprus low winter storms over the eastern coast of the Mediterranean. The focus is on changes in the nature of thunderstorms crossing the coastline from the sea into the northern and central parts of Israel, as manifested in their electrical activity. It is based on the Lightning Position and Tracking System (LPATS) measurements of lightning ground strikes during four winter seasons between 1995 and 1999. The spatial distribution shows a maximum of lightning ground strikes over Mount Carmel, possibly due to its topographical forcing. The annual variation shows a major maximum in January with two minor peaks, one in November and another in March, which can be explained by changes in the static instability of the atmosphere throughout the rainy period. The average fraction of positive ground flashes was found to be 6% and their average peak current +41 kA. The average peak current of negative ground flashes was −27 kA.

Larger frequencies of ground flashes were detected over the sea than over land during the study period. This is probably due to the large heat and humidity fluxes from the sea surface, which destabilize the colder air above and drive cloud convection. The annual distribution shows that during midwinter (December–January–February) there is higher flash density over the sea, while during autumn and spring the flash density is similar above the two regions.

The diurnal variation shows that the maximum in maritime lightning activity was at 0500 LST and over land at 1300 LST. The mean peak current of positive ground flashes was higher over land and of negative ground flashes, over the sea.

1. Introduction

There have been numerous studies of the differences in lightning characteristics occurring over continental and oceanic areas. Though it is clear from global studies that most lightning activity takes place over land (Turman and Edgar 1982; Orville and Henderson 1986; Christian et al. 1999), a considerable amount of lightning activity takes place over the oceans and along coastal areas. There are maritime regions such as the Gulf Stream in the Atlantic and in the South Pacific Ocean near Australia, where lightning activity appears frequently. Biswas and Hobbs (1990) showed that the average frequency and strength of ground lightning flashes over the Gulf Stream, off the Carolina coast, was greater than over the adjacent land.

Different circumstances generate thunderstorms in each type of area, and they encompass synoptic, microphysical, and geographical conditions. Orville and Henderson (1986) found that continental storms produce more lightning than maritime storms, and showed that the monthly ratio of continental to oceanic flashes ranges from 2.2 to 4.2. Christian et al. (1999) analyzed Optical Transient Detector (OTD) data for the years 1995–96 and found that 82% of the detected lightning occurred over land and only 18% over the oceans. Boccippio et al. (2000) focused their study on flashing individual storms in the tropical zone and found a factor of 2 between the mean flash rates observed by the Lightning Imaging Sensor (LIS) and the OTD, over land and over the ocean. Turman and Edgar (1982) used the optical sensors on the Defense Meteorological Satellite Program (DMSP) satellites to study the diurnal variation of global lightning activity. Their results showed that at dawn, 37% of the lightning flashes were related to oceanic storms and 63% to continental storms, while at dusk, only 15% of the global activity was oceanic. This reflects the differences in the diurnal evolution of the convective available potential energy (CAPE) that drives deep convection and the subsequent lightning activity (Williams 1992). Williams et al. (2000) and

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Seity et al. (2000) also observed different diurnal evolutions of electrical activity over both of the domains, and the afternoon peak of flash rate appeared only over land. Ushio et al. (2001) analyzed data from the LIS on the Tropical Rainfall Measuring Mission (TRMM) satellite and reported that of their database of 5529 events with more than 4 flashes per minute, only 14% occurred over oceans.

Lately, Füllekrug et al. (2002) found that particularly intense negative lightning discharges with absolute charge moments larger than 2 kC km occur more often over the oceans than over the continents.

Several explanations for the differences in the electrical behavior of continental and maritime storms have been proposed. It is believed that the dominant charge separation mechanism in thunderclouds is the noninductive ice–ice process (Williams 1989), shown in laboratory experiments (Jayarante et al. 1983) to have a strong dependence on the terminal velocities and sizes of the interacting ice and graupel particles (Ziegler et al. 1991). The growth rate of these particles is closely related to the supersaturation inside the cloud, which is correlated with the strength of the cloud updraft (Rogers and Yau 1989). Therefore, the lower vertical velocities found in thunderclouds over the sea (Zipser 1994; Zipser and Lutz 1994) should be manifested in weaker updrafts, a slower cloud evolution, less efficient charge separation, and an overall reduction in the charge buildup within the clouds. This effect was shown in the modeling work of Takahashi (1984), Ziegler et al. (1991), and Norville et al. (1991). Williams (1992) proposed that differences in the thermodynamics of the atmosphere in both domains, which can be expressed by their respective CAPE values, lead to differences in cloud evolution and electrical structure. He found that the CAPE in the environment of maritime storms was lower by a factor of 2 or more compared to continental storms. The effect of CAPE was further studied by Randell et al. (1994) who modeled storms developing in areas with high, moderate, and low CAPE values. The storms that developed in a high-CAPE environment were considerably more electrified than the other two cases. Large CAPE values induced larger updrafts, which produced more graupel and snow particles, accelerated their growth, and enhanced their collision rates. This also shifted the level of charge reversal (Takahashi 1984) to lower and warmer altitudes in the storm, which increased the vertical separation between opposite charge centers and reduced the neutralization effect that may occur when this level is found higher up in the clouds.

Another possible explanation may be the difference in the cloud condensation and ice nuclei spectrum in maritime and continental environments. The concentration of cloud condensation and ice nuclei is very often lower over the open sea than over land. As a result, the difference in the size distributions of drops and ice crystals in the developing clouds (in both areas) will have significant effects on the rapidity in which particles grow and collide, and separate electrical charges. Takahashi (1984) ran several numerical experiments in order to explain the observed differences in the electrical activity in clouds developing over land and sea. He found that when storms had low concentrations of ice nuclei, graupel particles grew more slowly and charging occurred in later stages of the cloud life cycle. Such low concentrations of ice nuclei are often found in maritime clouds.

The reviewed explanations clearly indicate that microphysical and cloud-scale dynamical processes are closely intertwined and that the differences in lightning activity in maritime and continental clouds is a reflection of other, more fundamental, differences.

2. The Mediterranean Sea

As one of the major centers of electrical activity in the Northern Hemisphere winter (Orville 1981; Christian et al. 1999), the Mediterranean Sea provides an exceptional and interesting region for studying the differences between land and sea lightning characteristics.

Unlike the oceans, the Mediterranean is a rather small body of water surrounded by three major continents: Africa to the south, Asia to the east, and Europe to the north. It covers an area, including the Sea of Marmara but excluding the Black Sea, of about 970 000 mi^2 (2 512 000 km^2). Space-based observations (Christian et al. 1999) clearly show that thunderstorms occur frequently over the Mediterranean Sea and in coastal areas throughout the winter (December–January–February), almost depicting the contours of its shorelines (http://thunder.msfc.nasa.gov/).

Israel is located on the eastern coast of the Mediterranean Sea, and experiences frequent storms and lightning activity during winter. Relatively few studies of winter thunderstorm activity over the eastern Mediterranean region have been made. Levin et al. (1996) and Yair et al. (1998) reviewed the meteorological conditions for thunderstorm development in Israel in detail. The most common synoptic setting for electrical activity is the passage of Cyprus lows (see Fig. 1), cyclones that originate in southern Europe and travel over the northern part of the eastern Mediterranean Sea (Alpert et al. 1990). Cold air masses that originate in Europe are modified by the influence of the warmer water of the Mediterranean Sea, leading to 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 and, after its passage, within the cold air mass. The thunderclouds in these cases develop over the sea and are driven eastward past the coastline onto the land by the westerly flow (Shay-El and Alpert 1991). Mechanical interactions (e.g., friction) between this westerly flow and the eastern coastline of the Mediterranean and the topographic features over land, together with thermal effects related to the sea–land interaction, are expected to shape a unique

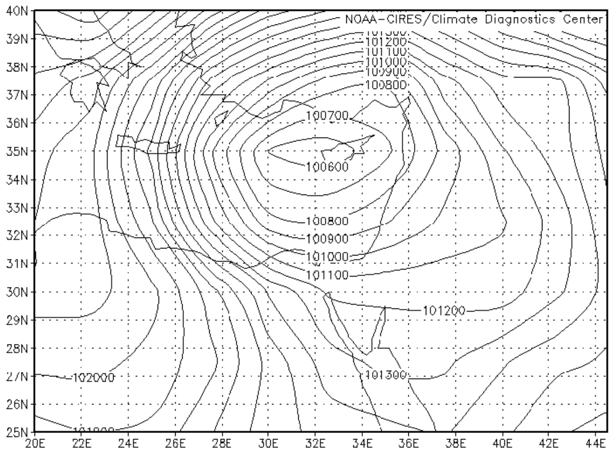

FIG. 1. A typical Cyprus low synoptic system. The sea level pressure (Pa) 0000 UTC, 18 Jan 1996, provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at http://www.cdc.noaa.gov/.

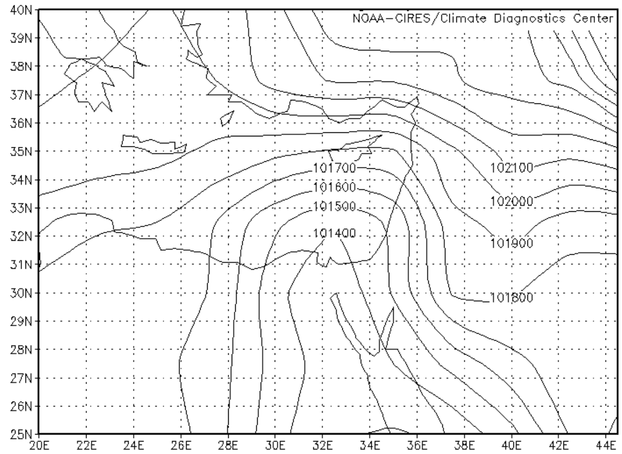

FIG. 2. A typical Red Sea trough synoptic system. The sea level pressure (Pa) 0000 UTC, 2 Nov 1994, provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, CO, from their Web site at http://www.cdc.noaa.gov/.

spatial and temporal distribution of lightning intensity over the study area. In addition to the Cyprus low, another cyclonic system produces thunderstorms over the study region. This is the Red Sea trough (e.g., Dayan et al. 2001; Kahana et al. 2002), defined as a surface low pressure trough extending from eastern Africa along the Red Sea toward the Middle East, mainly in the fall season (e.g., Ashbel 1938), exemplified here in Fig. 2. This type of disturbance differs from the Cyprus low in several aspects, among which are the spatial distribution of the thunderstorm activity and the absence of a westerly flow in the lower levels. Unlike the thunderstorms associated with Cyprus lows, which are confined to the northern half of Israel, those associated with the Red Sea troughs occur all over the country, but mainly over its southern part. The absence of westerly flow near the surface makes the interactions associated with the Cyprus low, mentioned earlier, irrelevant or totally absent in the case of the Red Sea trough. Furthermore the moisture sources for the convective clouds associated with the latter are found mainly in the midtroposphere (e.g., Dayan et al. 2001), implying a further weakening of the effects associated with the underlying surface conditions.

Harel et al. (1996) analyzed Lightning Position and Tracking System (LPATS) data for 1994–95 and found that the annual ground flash density varies greatly, from 0.5 km^{-2} in southern Israel to 3.5 km^{-2} near Haifa Bay. Levin et al. (1996) studied the relation between wind shear and the occurrence of positive ground flashes in Tel Aviv thunderstorms. Yair et al. (1998) presented the lightning characteristics in the Tel Aviv area based on CGR3 lightning flash counter (Mackerras 1985) for the period 1989–96. The annual flash density was found to be $4.7 \pm 2.3\ \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$. Altaratz et al. (2001) combined the data measured by meteorological radar with the LPATS lightning measurements to analyze the electrical properties of thunderclouds over Israel. The results showed that in winter, rain clouds became thunderclouds if their radar 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 isotherms was larger than 35 dB*Z*.

The purpose of this paper is to examine the differences in the electrical activity of storms over the sea surface and over land, and the changes in the nature and characteristics of the electrical activity of the storms during their passage eastward from the sea onto land areas. Taking into consideration the expected coastal and orographic effects associated with Cyprus lows, we confine our present study to the thunderstorms that occurred during the passage of this type of system. These circumstances are not unique to the Mediterranean Sea and also occur in other places around the world, such as western Japan, coastal areas in Ireland, France, and Portugal. The relatively small uncertainty resulting from the exclusion of lightning days associated with Red Sea trough can be seen in Table 1 (only 4% of the days). The table presents the total number of lightning days per month for each season compared to the Cyprus lows lightning days. The total percentage for the four seasons shows that the exclusion of Red Sea trough days from our study sample implies a reduction of 0%–5% of the lightning days in most of the year, except in November, where a 10% reduction is calculated.

3. Instrumentation and methodology

Observations of ground lightning strikes including time, location, polarity, and peak currents were obtained from the LPATS operated by the Israeli Electrical Company since 1994. During the study period (1995–99), the system was based on five measuring stations and a central processing unit located near Mount Carmel in

TABLE 1. The total number of lightning days per month compared to the Cyprus lows lightning days (marked C.L) per month, for each season and for the four seasons together. Note that the Cyprus lows days are 96% of the total lightning days.

Season		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1995–95	Tot	11	4	20	12	19	14	17	10	22
	C.L	11	4	19	11	19	14	17	10	21
1996–97	Tot	12	16	17	24	18	10	14	5	6
	C.L	12	16	13	24	15	10	13	5	6
1997–98	Tot	1	15	15	18	22	15	17	19	9
	C.L	1	13	13	17	21	15	17	19	9
1998–99	Tot	7	5	17	18	20	11	11	11	6
	C.L	7	5	17	17	20	11	11	11	6
Four seasons	Tot	31	40	69	72	79	50	59	45	43
	C.L	31	38	62	69	75	50	58	45	42
	%	100	95	90	96	95	100	98	100	97

Haifa. The small area of Israel and its elongated shape forced a unique configuration of almost a straight line between the detectors. These are located in Eilat, Ashkelon, Tiberias, Nahariya, and Jerusalem (see Fig. 3).

The detection efficiency of the system depends on the location of the storm relative to the network. Evaluations of similar systems around the world gave an overall efficiency of 70%–90% for ground flashes: Finke and Hauf (1996) described the LPATS system in southern Germany with six receiving stations separated by an average distance of 200 km, and Pinto et al. (1996) reported of the LPATS system in southeastern Brazil with four detection stations separated by an average distance of 300 km. The accuracy of any time-of-arrival-based system such as the LPATS is dependant on the time synchronization between detectors, and is generally better than 1 km (MacGorman and Rust 1998). Harel et al. (1996) have shown that the detection efficiency of the LPATS in Israel was consistent with the specifications over the entire land area of Israel and westward toward the Mediterranean Sea, where most storms arrive from. There are areas within Israel that exhibit poor coverage by the LPATS, with lower detection efficiency than that estimated; the Judean desert east of Jerusalem may be an example of such a region. However, so as not to reduce the integrity of the calculated flash densities, we included this area as it has only a minor effect on the results.

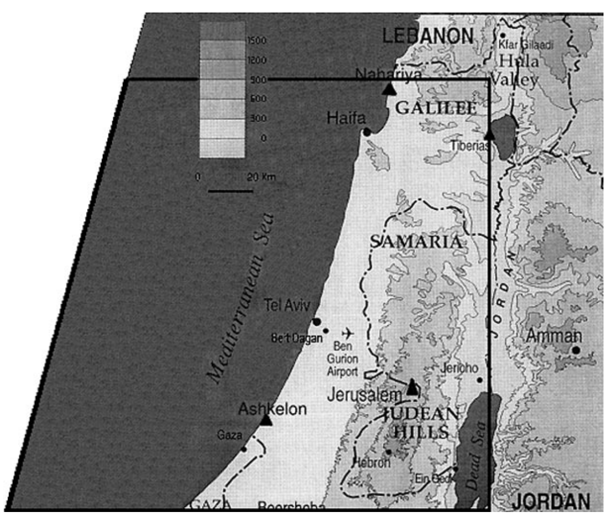

FIG. 3. Area of interest (inside the polygon). The antennas of the LPATS system are marked by triangles.

We focused on the northern and central parts of Israel and on an equal area over the Mediterranean Sea bounded by latitudes 31.3° and 33.1°N (Fig. 3). The total area is 27 075 km^2 and for purposes of comparison, it was equally divided between sea and land. In this analysis we disregarded positive ground flashes with peak currents lower than 10 kA because they could be signals of cloud flashes (Cummins et al. 1998), which are not discussed in the present study.

Cyprus low event selection was performed by examining sea level pressure maps and wind direction in the 925-mb pressure level, during the thunderstorm days, taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalney et al. 1996; Kistler et al. 2001). We selected only those events in which the centers of the lows were found to the west or north of Israel and with a southwest to northwest wind in the 925-mb level.

4. Results

This section will begin with the general description of the characteristics of electrical activity during the passage of Cyprus lows over the eastern Mediterranean (section 4a). The second part (4b) will deal with the differences between lightning activity over land and sea.

a. *General description of lightning activity over the eastern Mediterranean*

1) ANNUAL DISTRIBUTION

The LPATS detected 32 383 ground flashes over the study area during 425 thunderstorm days in four winter seasons between 1995 and 1999. Since the lightning activity period in the study region begins in September

TABLE 2. The annual total ground flashes and the averaged ground flash density during Cyprus low events (calibrated data per sample year).

Season	1995–96	1996–97	1997–98	1998–99
yr^{-1}	6240	12 980	9773	3390
km^{-2} yr^{-1}	0.23	0.49	0.37	0.12

and ends in May, it is best to define as a ‘‘lightning year’’ the period beginning in July and ending in June of the following calendar year. In this way, each lightning year contains an entire season.

The total number of ground flashes and the average ground flash densities over the study area for the four lightning years (1995–99) are presented in Table 2. It is clear that the interannual variability is comparable to the annual average itself. The densities are fairly low, compared to previous reported values (Yair et al. 1998), probably due to the fact that the present results include only ground flashes and that they are averaged over the entire area (27 075 km^2), including regions with very low densities (see below). Orville et al. (2002) found that the flash density over North America varies between 0.1 km^{-2} yr^{-1} over the north of Canada to 9 km^{-2} yr^{-1} in Florida.

Figure 4 displays the spatial distribution of flash density, using 20 km^2 grid boxes, for the study period. The value obtained for the Tel Aviv area is 0.9 km^{-2} yr^{-1}, consistent with previous values reported by Yair et al. (1998), who used CGR3 lightning-counter data, and obtained a total flash density of 4.7 $\pm$ 2.7 km^{-2} yr^{-1} (cloud and ground flashes) in that area. The average ratio of 2.5 for cloud flashes to ground flashes (Yair et al. 1998) implies that the ground flash density is $\sim$1.3 km^{-2} yr^{-1} for the same location. Our new measured density is somewhat lower due to the fact that the current dataset does not include flashes that occurred during synoptic settings other than Cyprus lows (e.g., active Red Sea trough).

The highest flash density, that is, 2.5 km^{-2} yr^{-1}, was detected over Mount Carmel near the coastal city of Haifa, 100 km north of Tel Aviv. There are a few possible causes for this finding. The mountain acts as a topographical obstacle, which offers a significant orographic lifting mechanism that enhances convection for the air coming from the sea towards the land over the western slopes (see Fig. 3 for a graphic representation of the topography near Mount Carmel). Finke and Hauf (1996) found a similar effect when the maximum of lightning activity in southern Germany was measured over the Black Forest Mountains (10 km^{-2} yr^{-1}, cf. 2 km^{-2} yr^{-1} in most other parts of southern Germany). The stronger updrafts in the clouds located near mountains create more developed clouds with larger amounts of ice and water drops that eventually enhance the charge separation process. The latter is based on the assumption that the main charge separation process in clouds is the noninductive mechanism of collisions of graupel particles and ice particles (Reynolds et al. 1957; Takahashi et al. 1999). Solomon and Baker (1994), who used model data, established that the cloud updraft must exceed a threshold value for a minimum period of time in order for the cloud to become electrified. Rosenfeld (1986), who studied rain clouds in Israel, found that convective clouds are formed 15 km upwind of the topographical obstacle and that the maximum rain rate occurs above the mountain itself. In our previous studies (Altaratz et al. 2001) we found that the maximum lightning activity in winter thunderstorms appears 5–10 min before the peak rain rate is observed at the ground (Altaratz 1997). Therefore, the location of the maximum lightning density can indeed be expected to occur near the western slope of Mount Carmel. Another possible reason for this observed enhancement of electrical activity may be airflow convergence due to the urban heat island effect caused by the industrial area of Haifa Bay. Another possible factor may be the air pollution produced in that area, which is one of Israel’s major petrochemical centers, with many oil refineries and heavy industry. Air pollution particles are expected to modify the microphysical properties of the clouds and subsequently affect the charge separation processes and the onset and nature of lightning activity. Orville et al. (2001) and Steiger et al. (2002) discussed the high flash density near the urban areas of Houston, Texas, and suggested that elevated flash densities could result from this urban influence of heat and pollution. A similar effect was noted by Ezcurra et al. (2002) over the city of Bilbao in Spain.

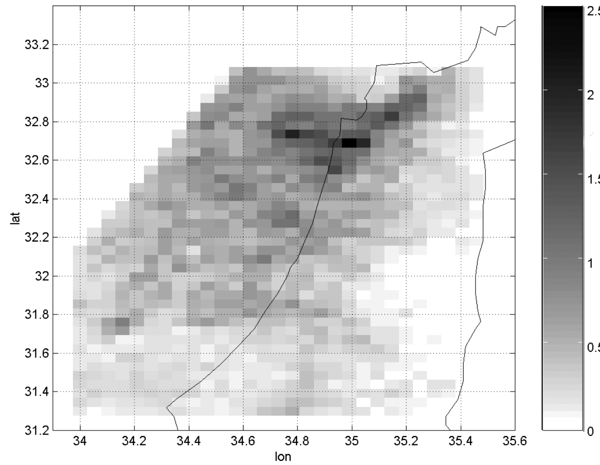

FIG. 4. Geographical distribution of mean seasonal ground flashes density during Cyprus low events for 1995–99 (km^{-2} yr^{-1}).

2) MONTHLY VARIATION

A histogram of the monthly lightning hours is shown in Fig. 5. The Cyprus lows thunderstorm season is well defined between the months of October and April, with very little activity in the border months of September and May.

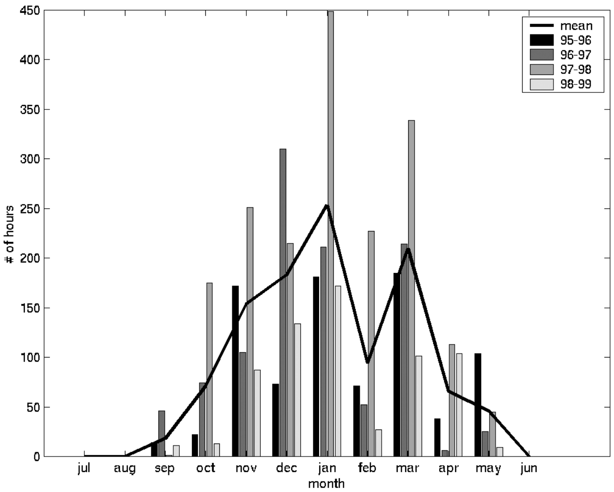

FIG. 5. The lightning hours during Cyprus low events, as a function of month for four seasons 1995–96, 1996–97, 1997–98, 1998–99 (by columns) and the mean value per month (black line).

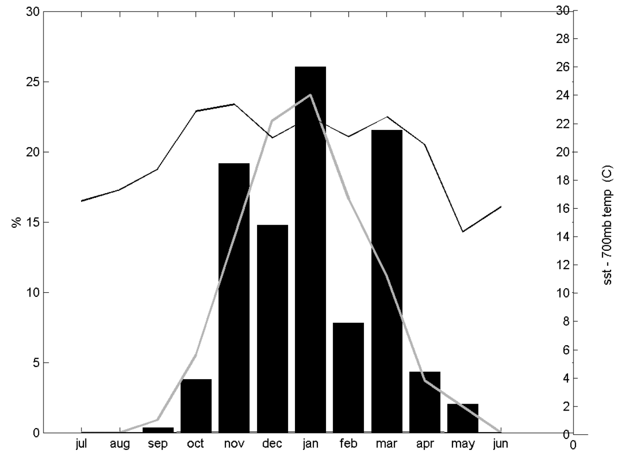

FIG. 6. Lightning monthly distribution during Cyprus low events (columns) and accumulated rain distribution (gray curve) and the difference between SST and 700-mb temperature (black curve).

Lightning activity in the eastern Mediterranean peaks during winter, the time of the global minimum of electrical activity in the Northern Hemisphere (Orville and Henderson 1986). The strongest lightning activity occurs between November and March and the mean maximum monthly lightning hours occurs in January (Fig. 5). The interannual variability of lightning hours is rather large, and the maximal storms duration does not always occur in January. It seems that the location of Israel in the eastern corner of the Mediterranean results in an irregular storm occurrence pattern during winter. The entire Middle East region is influenced during winter by a combination of subtropical highs and midlatitude lows. The relative trajectories of the latter determine whether the weather is going to be fair or stormy. The mean monthly lightning hours distribution (the black line in Fig. 5) shows a local maximum in March but the monthly flash density distribution (Fig. 6) shows a pattern with two secondary maxima, in November and in March. The duration of the storms (represented by the monthly hours) and the intensity of the storms (represented by the monthly flash density) are not similar. Trying to explain the two maxima we calculated an instability index, which is shown in Fig. 6. The black curve in this figure is the average difference between the sea surface temperature (SST) and the temperature at the 700-mb pressure level for the thunderstorm days included in the study period. This temperature difference is assumed to serve as an index for the instability of the lower midatmosphere. A large index reflects an unstable atmosphere. The gray curve is the average long-term monthly precipitation distribution calculated for Hafetz-Haim (a meteorological station 15 km from the coast) based on measurements taken between 1961 and 1990 (Goldreich 1998). The lightning density histogram is similar to the Cyprus lows frequency histogram (Sharon and Ronberg 1988), but differs from the distribution of average monthly precipitation. The amount of rain increases until the middle of the rainy season in January and then decreases toward the end of the season, forming a bell-shaped distribution. Approximately 15% of the annual rainfall occurs in the fall (September–October–November) and about the same percentage in the spring (March–April–May). The monthly flash density histogram in Fig. 6 shows a different pattern. The two secondary maxima, in November and in March can be explained by the variation of the previously mentioned instability index during the lightning year, which also has two secondary maxima in the same months. This emphasizes the crucial role of the lower-level instability for electrical activity. Regarding the distribution along the year, 26% of the annual amount of lightning flashes occurs in the fall season (September–October–November) and only about 11% in the spring months (March–April–May). Since the seawater is colder in spring than in the fall, it produces weaker vertical atmospheric instability in the former than in the latter. Another thing is that the relative part of the autumnal electrical activity (26%) is larger than that of the precipitation in these months (15%). This means that the amount of rain per lightning flash is smaller during the autumn thunderstorms compared to the midwinter storms. A possible explanation for this observation may be related to the difference in the degree of vertical development of convective clouds in autumn and winter, which results from the difference in the height of the tropopause. In autumn, when the tropopause is higher than in the winter, clouds are more vertically developed and are thus capable of more intensive electrical activity (Price and Rind 1993; Ushio et al. 2001).

3) DIURNAL VARIATION

The diurnal variation of the electrical activity is presented in Fig. 7, in terms of lightning percentage as a

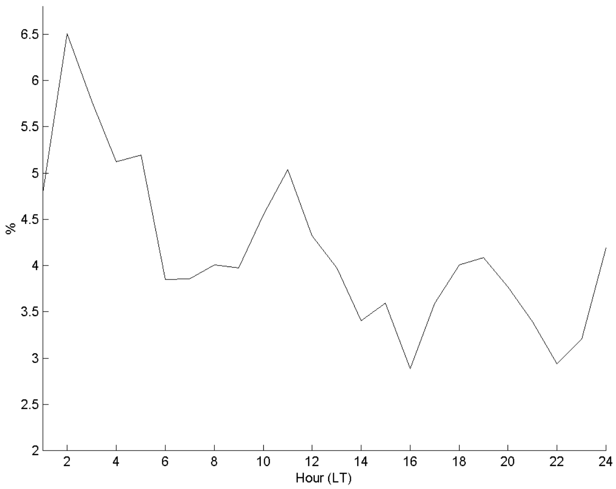

FIG. 7. The percentage of ground flashes during Cyprus low events as a function of local time.

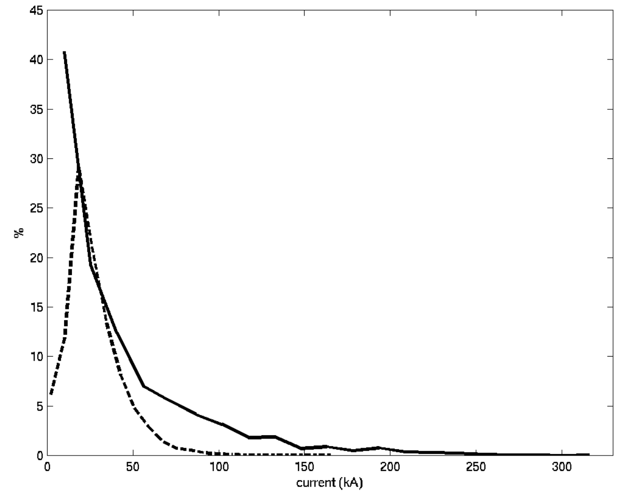

FIG. 8. The distribution of peak currents of positive (solid line) and negative (dotted line) ground flashes during Cyprus low events over the whole region.

function of time of day. The main peak occurs at 0200 LST with two secondary peaks at 1100 and 1900 LST. By comparison, the maximum electrical activity of thunderstorms over Europe and Africa occurs around 1400 UTC (Whipple and Scrase 1936). At this time (1600 LST) we found a minimum in the eastern Mediterranean. The peak in the early afternoon over the large continents reflects the dominance of the heating of the earth's surface as a convective thunderstorm generator. In the eastern Mediterranean almost all thunderclouds are associated with synoptic-scale forcing, which probably smooths out the diurnal signals. Orville et al. (2001) also pointed to the fact that wintertime flashes over Texas do not occur during a preferred time of day, unlike the summer thunderstorms, which tend to occur in the afternoon. In section 4b(3), the differences in the diurnal evolution of thunderstorms over land and sea are further discussed.

4) POSITIVE GROUND FLASHES

The average percentage of positive ground flashes for the lightning season is 6%. This value is lower than the 16% that was reported by Yair et al. (1998) for the Tel Aviv area. The reason for this difference may be the exclusion of the abundance of positive ground flashes during Red Sea trough situations that were included in their study. This hypothesis will be checked in a future study. The current value is lower than what was previously published for winter thunderstorms around the globe. Orville et al. (1987) found that along the east coast of the United States, the monthly percentage of positive ground flashes for June 1984 through May 1985 was 50%. Hojo et al. (1989) found 60% for the west coast of Japan, and Kitagawa and Michimoto (1994) found 33% for winter thunderstorms in Japan.

The mean monthly percentage of positive ground flashes for the four lightning years was not constant during the year and also varied for the same month from year to year. The average percentage of positive ground flashes (of all ground flashes) per month ranges between 2% and 22%. Orville and Huffines (1999), who studied the monthly percentage of positive lightning for the United States, found 14%–24% for the winter months. Levin et al. (1996) noted that an increase in the percentage of positive ground flashes in the Tel Aviv area may be related to the presence of a large wind shear, inducing a tilted-dipole structure in the clouds (Brooks et al. 1982).

5) PEAK CURRENT

The average peak current of negative ground flashes, which were detected over the entire study area, is −27 kA (the median peak current is −24 kA). For positive ground flashes, the average is +41 kA but the median peak current is only +23 kA. Using the National Lightning Detection Network (NLDN) system covering North America, Orville et al. (2002) found a median negative peak current of 16.5 kA and a positive of 19.8 kA. These values reflect the considerable differences between the current distributions of these two types of ground flashes. Figure 8 presents the distributions of peak currents for positive (solid line) and negative (dotted line) ground flashes. Only 5% of the negative ground flashes have a peak current larger than −60 kA. The maximal value measured is −165 kA. The distribution of positive flashes is much wider and the peak is in the range of the lowest currents. Since we excluded from the analysis flashes with currents smaller than +10 kA, the minimum appears at 10 kA. Almost 23% of the flashes have a peak current larger than +60 kA. The maximal value measured is +316 kA. The values of the average peak currents we report here are comparable to measurements in thunderstorms in other places around the world and

TABLE 3. The annual total ground flashes and averaged ground flash density during Cyprus low events over sea and land (calibrated data per sample year).

Season		1995–96	1996–97	1997–98	1998–99
Sea	yr^{-1}	4124	7442	6832	1723
	$km^{-2}\ yr^{-1}$	0.30	0.54	0.50	0.12
Land	yr^{-1}	2116	5538	2941	1667
	$km^{-2}\ yr^{-1}$	0.15	0.40	0.21	0.12

to previous measurements of lightning in Israel by LPATS reported by Harel et al. (1996). They found a mean peak current of −33 kA for negative ground flashes and +42 kA for positive ones. In the Spanish Basque country area, Ezcurra et al. (2002) found a mean peak current of −27 kA for negative ground flashes and +55 kA for positive ones. On the western coast of Japan, Hojo et al. (1989) found median peak currents of −30 kA for negative ground flashes and +60 kA for positive ground flashes. In southern Germany, using a similar LPATS system, Finke and Hauf (1996) found a mean peak current of −25.5 kA for negative ground flashes and +32.6 kA for positive ones. All these values are in agreement with earlier findings of current distributions for positive and negative ground flashes reported by Berger et al. (1975).

b. Lightning characteristics over land and sea

Figure 3 shows the division of the study area between land and sea. During the study period, LPATS detected 12 262 flashes over land and 20 121 flashes over the sea.

1) ANNUAL FLASH DENSITY

Table 3 presents the annual total ground flash counts and the averaged ground flash density detected over sea and land. The densities are calculated over half of the general area (13 538 km^2). The values over the sea are higher in all 4 yr by a factor that varied between 1.03 and 2.4 compared to land. This is rather unusual compared to oceanic and continental lightning activity elsewhere around the globe.

However, some areas around the world have a similar pattern. Several studies of winter lightning in Japan have shown that ground strikes occur primarily to the sea surface (Hojo et al. 1989). Similar results were reported by Biswas and Hobbs (1990) for the Gulf Stream. The average frequency and intensity of ground lightning flashes from rainbands over the water in the Gulf Stream were greater than these over the adjacent land. In all these cases, lightning activity is attributed to the large fluxes of heat and water vapor from the warm waters of the sea surface to the colder air above.

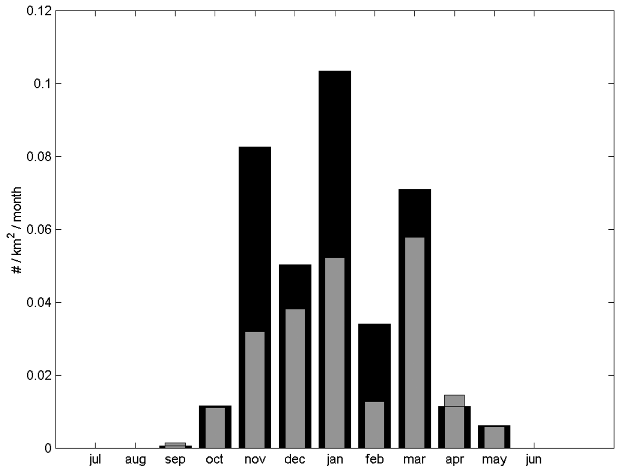

FIG. 9. The monthly flash density above the sea (black columns) and above land (gray) during Cyprus low events, for the years 1995–99.

2) MONTHLY FLASH DENSITY

Figure 9 compares the monthly flash density above the land area (gray columns) and the sea (black columns). Clearly the distribution of the electrical activity during the year over the two regions is not identical. In midwinter the density is considerably higher over the sea. On the other hand, during the fall months, September–October, and the spring months, April–May (the beginning and end of the thunderstorm season, respectively), the flash densities over land and sea are almost equal or even slightly higher over land. This difference may be explained by the temperature contrast between the cold air masses originating from Europe and the relatively warm surface of the eastern Mediterranean Sea. This contrast is maximal in midwinter. As a result, the instability that is built up within these air masses as they move over the water increases rapidly and the thunderclouds develop at an earlier stage while they are still far from the coastline. In the transition seasons this thermal contrast is weaker and the convection develops much slower and at a later stage, when the clouds are closer to the coastline or over the land itself.

3) DIURNAL VARIATION

Figure 10 shows a comparison between the variation of the activity during the day over the sea (solid line) and over land (dotted line). The peak of maritime activity is at 0500 LST (0300 UTC) and that of continental activity at 1300 LST (1100 UTC). The main peak of the lightning activity over land occurs earlier than the afternoon peak reported by Boccippio et al. (2000) and Seity et al. (2000).

A few factors may contribute to the existence of this peak in the early morning hours over the sea. The curved shape of the Mediterranean coastline beginning in Egypt toward the city of Gaza and northward, leads to a con-

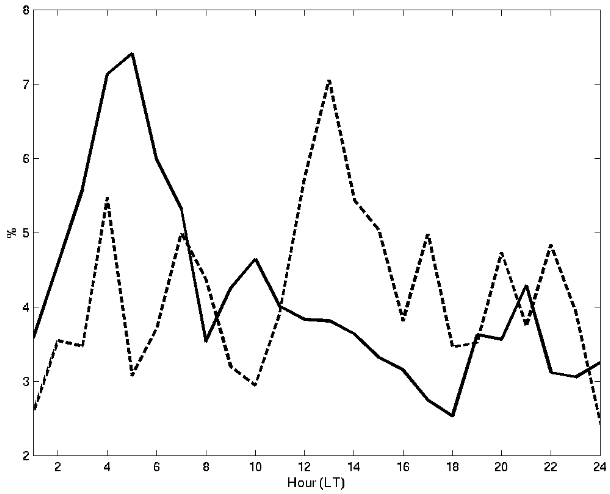

FIG. 10. The percentage of ground flashes during Cyprus low events, as a function of local time for the sea (solid line) and for land (dotted line).

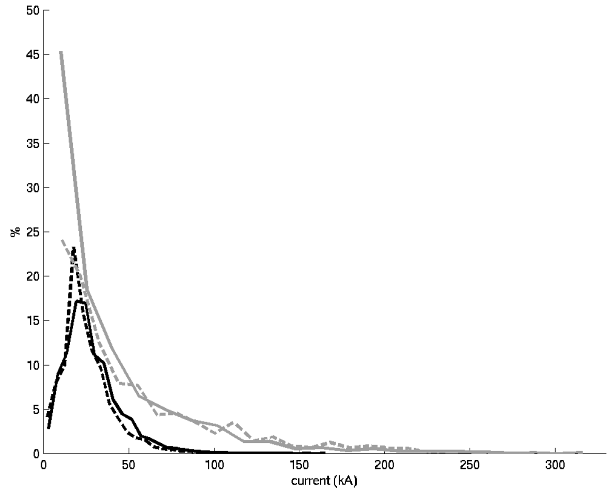

FIG. 11. The distribution of peak currents of negative ground flashes over land (dotted black line) and over the sea (solid black line) and of positive ground flashes over land (dotted gray line) and over the sea (solid gray line) during Cyprus low events.

vergence of eastern and southeastern land breezes over the sea. The maximal intensity of the land breeze occurs in the early morning hours (when the temperature difference between the land and the sea is maximal) enhancing the lifting mechanism of the air within the planetary boundary layer and thus increasing the probability of cloud development and lightning activity. Khain et al. (1993) and Furshpan (1997) discussed the importance of the land breeze in the development mechanism of rain clouds near the coast. The convergence of the prevailing synoptic wind (which is normally westerly in these synoptic situations) with the continental breeze (easterly southeasterly) above the sea enhances convection.

4) PEAK CURRENT

The average peak current of negative ground flashes is −28 kA over the sea (the median is −25 kA) and −25 kA over land (the median is −22 kA). Figure 11 presents four distributions: the solid black line for negative flashes over the sea and the dotted black line over land. The maximum of the distribution, in the range of 18–24 kA is higher over land (difference of 5%) but the larger currents are more frequent over the sea. These findings are in accordance with those reported by Füllekrug et al. (2002), who found that intense negative lightning discharges occur more often over the oceans in coastal areas than over the continents.

For positive ground flashes, the mean peak current is +38 kA for lightning over the sea and the median is +20 kA (solid gray line in Fig. 11) and +49 kA for land (the median is +32 kA; dotted gray line). The maximum of the distribution is higher over the sea (10 kA, 45% compared to 24%). However, there is little difference between the two tails of the distributions.

It seems that the mean peak current of positive ground flashes is higher over land and for negative ground flashes it is higher over the sea. This contrasts with the findings of Biswas and Hobbs (1990), who showed that the strength of the positive ground flashes is systematically greater over the Gulf Stream than along the coastline. Seity et al. (2000) found that the average peak current is higher over the sea for both positive (by 5 kA) and negative ground flashes (by 12 kA).

5. Summary

The present research focused on the differences in properties of lightning that occurs during winter thunderstorms over the coastal region of the eastern Mediterranean. We studied storms, as they were moving eastward over the sea across the Israeli coastline toward land, with an emphasis on ground flash frequencies and intensities. Remarkable differences in the diurnal variation, peak currents, and densities were found, which point to the uniqueness of these winter thunderstorms, especially across the land–sea interface. Most of the planetary lightning activity in the Tropics is driven by solar heating-induced convection, and hence follows a pronounced diurnal cycle that peaks in the local afternoon (reflected in the Carnegie curve). Winter lightning activity in the eastern Mediterranean, on the other hand, was found to peak at night and during the early morning. This suggests that it may be driven by specific local factors, which include

1) The synoptic-scale factor—that is, the timing of the passage of cold fronts associated with Cyprus lows. The linkage between these cyclonic systems and lightning occurrence is reflected in the similarity of their annual distributions. The weak daily maximum found over land, as compared with the sharp daily

maximum commonly observed over continents, reflects the relatively high significance of synoptic-scale factors in initiating and maintaining convection in our region, over local factors, which prevail over land areas.

2) The thermodynamic factor—that is, the lapse rate between the sea surface temperature and the temperature at the 700-mb pressure level (around 3000 m), which reflects the degree of static instability. This condition is closely linked to the flow in Cyprus lows, which transports cold air masses over the relatively warm water of the Mediterranean Sea (e.g., Alpert et al. 1990), implying the development of static instability, which eventually drives deep convection. The maximal temperature contrast between the cold European air masses and the warm surface of the sea in midwinter results in early development of thunderclouds and intense lightning activity over the sea. This explains the higher flash density found over the sea during midwinter, unlike the almost equal densities found over land and sea during the autumn and spring seasons.

   In addition to these factors, there are mesoscale factors that modulate the spatial and temporal distribution of the electrical activity.

3) Orography—The Mount Carmel ridge exerts a constraint that forces the westerly flow induced by Cyprus lows to ascend, and so amplifies the updraft and enhances convection. This effect, combined with that of the coastline itself, can explain the striplike maximum in lightning frequency oriented west–east that extends from the sea through Mount Carmel.
4) Sea–land temperature contrast—There is a nocturnal distinct maximum in lightning frequency over the sea, which is not found over land (Fig. 10).

The special circumstances under which the winter thunderstorms develop and move across the land–sea interface are manifested in the lightning characteristics reported in this work. They are not unique to Israel, and can possibly be found in other geographical locations such as Japan, France, Portugal, South Africa, and the American West Coast. Further comparative studies of winter lightning activity, which involve remote sensing and in situ measurements of cloud properties, may reveal even deeper similarities.

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