First reported case of Thunderstorm Asthma in Israel

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Abstract. We report on the first recorded case of thunderstorm asthma in Israel, that occurred during an exceptionally strong Eastern Mediterranean multicell-cell thunderstorm on October 25th 2015. The storms were accompanied by intensive lightning activity, severe hail, downbursts and strong winds followed by intense rain. It was the strongest lightning-producing storm ever recorded by the Israeli Lightning Detection Network since it began operations in 1997. After the passage of the gust front and the ensuing increase in particle concentrations, documented by air-quality sensors, the hospital emergency room presentation records from three hospitals – two in the direct route of the storm (Meir Medical Center in Kfar-Saba and Ha'Emek in Afula) and the other just west of its ground track (Rambam Medical Center in Haifa) showed that the amount of presentation of patients with respiratory problems in the hours immediately following the storm increased compared with the average numbers in the days before. This pattern is in line with that reported by Thien et al., (2018) for the massive thunderstorm asthma epidemic in Melbourne, Australia. The increase in patient presentations to the emergency rooms persisted for additional 48-72 hours before going back to normal values, indicating that it was likely related to the multi-cell outflow. We discuss how the likelihood of incidence of such public-health events associated with thunderstorms will be affected by global trends in lightning occurrence.

1. Introduction.

Thunderstorms and lightning are natural hazards, lethal and destructive with important implications on human societies. They are often accompanied by severe weather, hail and flash floods that entail significant economic and human losses (Yair, 2018; Petrucci et al., 2019; Cooper and Holle, 2019). Public health effects of thunderstorms that are not related to direct lightning strikes of people may be the result of flooding, fallen trees, objects hurled by strong winds, impact of heavy hail, smoke from ignited forest fires and the consequences of disruptions to daily routines such as industrial accidents, loss of electricity, car accidents and limitation to air travel (Krausmann et al., 2011; Yair et al., 2018).

Research had shown that during the development stage of thunderstorms, updrafts carry surface aerosols and pollen particles into the cloud, where the high humidity and contact with liquid water causes pollen to rupture (Knox, 1993; Taylor et al., 2004a; Miguel et al., 2006; Vaidayanathan et al., 2006). At the mature stage of thunderstorm development, characterized by intense electrical activity and precipitation (typically lasting tens of minutes), downdrafts carry such pollen fragments to the ground. When the downdrafts impinge on the surface they diverge and the outflow enhances the concentrations of airborne particles by causing uplift of additional concentration of pollen and dust particles into the air. If such outflows occur in dry desert areas, this often leads to the formation of well-known dust-wall known as "Haboob" that makes the gust front clearly visible and is portrayed in many Youtube videos (Williams et al., 2007). The gust front - the storm scale boundary caused by the outflow from the thunderstorm – quickly spreads and diverges from beneath it and propagates along the storm track. The airborne pollen fragments and particles often release allergens in the size range < 2.5 micrometers that can be inhaled into the respiratory system and cause an acute allergic response. If occurring during the flowering season of specific plants, this may result in "*Thunderstorm Asthma*" epidemics (Bellomo et al. ,1992; Packe and Ayers, 1995; Venables et al., 1997; Wardman et al., 2002; Dales et al., 2003; D'Amato et al., 2016; 2017), which are expressed as severe respiratory problems, especially in sensitive populations (infants, senior citizens and people with prior allergic susceptibility). A thorough review of the present theories of thunderstorm asthma mechanisms is presented by Harun et al. (2019) and some unique cases are described below.

Grass pollen is a well-known cause of hay-fever and allergic asthma, and has been implicated as the cause of two cases of thunderstorm asthma epidemics, in Melbourne (1987/1989) and in London (1994). Knox (1993) discuss the fact that grass pollen is too large to penetrate into the lower airways and trigger the allergic response and suggested that osmotic shock of caused by rainwater led to the rupture of grass pollen particles and the release of the major allergen Lol p 5;

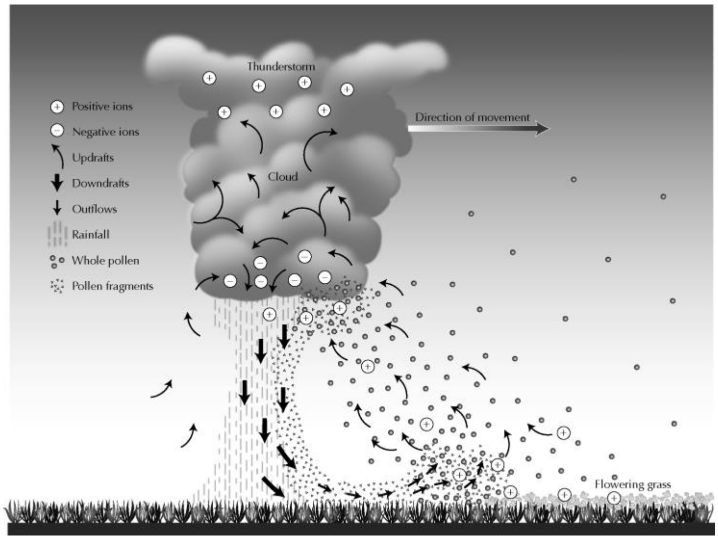

Figure 1: A schematic description of the mechanism that enhances the concentrations of airborne aerosols (either pollution particles or pollen) ahead of a mature thunderstorm (Taylor and Jonsson, 2004).

Nasser and Pulimood (2009) reviewed the role of fungal spores such as *Alternaria* in outbreaks of thunderstorm asthma and showed that the sudden increase in spore concentrations in the air following large-scale thunderstorm cold flows affects atopic, sensitized people, and may lead to asthmatic response. There are numerous reports from many countries about cases of thunderstorm asthma (Dabrera et al., 2012; Andrew et al., 2017; Beggs, 2017). For example, the Wagga-Wagga epidemic in Australia on October 30th 1997 led to 215 ED visits by asthmatic subjects with 41 hospitalizations, a fact that created an unusual burden on the health services there (Girgis et al., 2000). The most extreme case on record occurred in Melbourne, Australia, in November 2016 (Thien et al., 2018), when a thunderstorm asthma epidemic following a gust front induced by a multicell thunderstorm system resulted in more than 3000 presentations to Emergency Departments (ED) at hospitals for allergy and respiratory problems, with 10 fatalities (and see Table 1 in Harun et al., 2019). The allergic response of the population followed (or was prompted) by a chain-reaction commencing with the dynamics of the cold outflow from the thunderstorm. D'Amato et al. (2015) characterized the main aspects of thunderstorm-associated asthma epidemics (based on their Table 2): (a) The epidemics are limited to seasons when there are high concentrations of airborne allergenic and/or fungal spores. (b) There is a close temporal association between the start of the thunderstorm and the onset of the epidemics. (c) There are not high levels of pollution related gasses and particles during the thunderstorm asthma outbreak (d) People who stay indoors with windows closed are not affected and (e) there is a major risk for subjects who are not optimally treated for asthma; subjects with pollen-induced allergic rhinitis and without prior asthma are also at risk.

While this definition of thunderstorm asthma focuses on the allergic responses to airborne pollen or fungal spores, some reports consider other environmental factors such as humidity, temperature and pressure changes (Rossi et al., 1993; Ito et al., 1989). A chemical effect of lightning activity that may also play a role in thunderstorm asthma epidemics is the production of significant amounts of NO and O_3 near the surface. Ozone by itself is a potent oxidizer and is known to create severe respiratory response when inhaled (Molfino et al., 1991; Gleason et al., 2014). Indeed, Campbell-Hewson et al. (1994) considered several types of pollen and fungal spores, but also ozone concentrations and lightning, in the context of a thunderstorm asthma epidemic in Cambridge and Peterborough in southern England in June 1994. They reported an increase by a factor ~2 of ozone concentration (45 ppb compared with daily average of 28.7 ppb) and high pollen counts before the rain and concluded that the causes of the epidemic were likely multifactorial. It should be pointed out that although there were 37 lightning strikes in that region, the authors did not attribute the rise in ozone concentrations to lightning but rather to local pollution. This aspect of lightning activity was not considered in the present study.

A thorough review published by the World Allergy Organization (D'Amato et al., 2015) surveyed the expected changes in the occurrence of thunderstorm asthma and concluded that people with hypersensitivity to pollen allergy should be advised to stay indoors when there are clear indications that thunderstorm activity is expected. Such early-warning capabilities for lightning are becoming operational in some countries (for example the Lightning Potential Index [LPI] which is used in Weather and Forecasting Research model (WRF; Lynn and Yair, 2010; Lynn et al., 2012), but there seems to be a gap between forecasting lightning and administrating public-health warnings, and sensitive populations are not always effectively alerted when thunderstorms are expected.

2. Data Sources

We used data from various sources for studying possible correlations between meteorological conditions, lightning occurrence, aerosol concentrations, pollen counts and respiratory illnesses for central Israel.

a. Lightning data was obtained from the Israeli Lightning Detection Network (ILDN) operated by the Israeli Electrical Corporation (IEC). The system and its capabilities are described by Shalev et al. (2011).

b. Meteorological data – temperature, humidity, wind and pressure data were obtained from the Israeli Meteorological Service (IMS) for selected stations throughout the country.

c. Aerosol data – we used the $PM_{2.5}$ and PM_{10} data that are collected routinely by the Ministry of Environmental Defense in Israel, that operates a national network of > 40 stations. These stations report particle concentrations at 5-minute intervals. That system also records Ground Level Ozone data.

d. Pollen data – The daily average pollen and spore concentrations (number/m^3) were obtained from the Ted Arison Laboratory for Monitoring Airborne Allergens at Tel-Aviv University. The species are listed in Appendix 1.

e. Hospital presentationpresentation records for patients with respiratory symptoms of specific ICD codes at the Emergency Room (ER) were collected from 3 Israeli hospitals for a specific list of allergy-related illnesses. Approval of the internal Helsinki committee in each hospital were obtained. The long-term averages were obtained from hospital records to establish the baseline.

3. Meteorological Conditions

The synoptic condition leading to the unusual event described here are summarized by Razy et al. (2018) and will be briefly described below. During October 24th 2015 the eastern Mediterranean was dominated by a Red-Sea Trough (RST, Ben-Ami et al., 2014), a low-pressure region extending from the south along the Red-Sea northward to the eastern Mediterranean. This system transported tropical air toward Egypt, Jordan, Israel, Lebanon and Cyprus in the lower-levels (850 hPa). At the upper-levels (500 hPa), a pronounced trough was situated with the axis slanted between Crete and Cyprus. This trough had two effects: one is a transport of tropical air by the south-southwesterly winds aloft and second is upward motion at the mid-levels, induced by positive vorticity advection ahead of this trough. Prior to the beginning of the storm, a cold front was noted west of the Israeli coast. At the same time a meso-scale cyclone was formed over the Sinai Peninsula and the southeastern Mediterranean, organizing the flow that advected moist air from the sea. During the morning hours of October 25^{th,} the cyclone, together with the cold front, moved toward inland. Around 07 UTC this multi-cellular cold front crossed central Israel, accompanied by extremely developed thunderclouds, with tops reaching 17 km height. The highly populated area of central Israel, extending from the coastal region inland, was subjected to torrential rains for 1-2 hours and large hailstorm with over 5cm diameter. Rain-gauge data obtained from the Israeli Meteorological Service show that in several places in central Israel the 10-minute rain rate exceeded 100 mm h^{-1} with a total of >50 mm in the entire event (constituting ~10% of the annual average). The intensity of the storm can be attributed, at least partly, to the tropical nature of the warm air transported from south by the RST, ahead of the storm. The supercell subsided upon reaching the Jordan rift in eastern Israel. The entire event caused 1 fatality, extensive flooding in several Israeli cities and agricultural damages. It also impacted the national electrical grid with power outages lasting up to 3 days in central Israel. This was the most powerful thunderstorm ever observed in Israel since the Israeli Lightning Detection Network (ILDN) became operational in 1997**.**

a. **Wind** – Based on the Israeli Meteorological Service data, the storm was typified by destructive south-westerly winds that exceeded 25 m s^{-1}, with gusts of >36 m s^{-1}, which can be attributed to the downbursts from the active cells. Figure 2 presents wind speeds measured at several locations. The distance from Tel-Aviv coast (purple line) to Hadera port (red line) is approximately 40 km, indicating a very wide gust front that swept across central Israel together with the movement of the active cells. The sustained high winds lasted for more than two hours, and caused a significant increase in amounts of airborne particulate matter (see below).

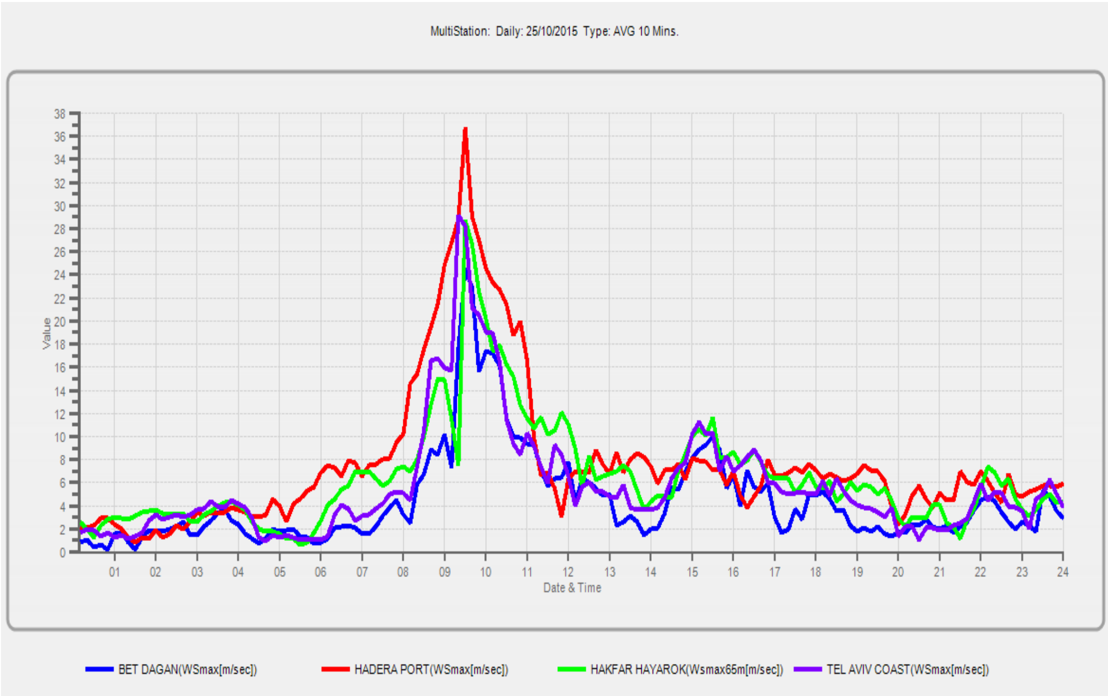

Figure 2: Wind speed at 4 different stations along Israel. Bet Dagan (in blue) is located 12 km southeast of Tel-Aviv. Hadera Port (red) is located on the coastline, 45 km north of Tel-Aviv. Hakfar Hayarok (green) is 5 km northeast of Tel-Aviv, and Tel-Aviv coast (purple) is located on the Mediterranean coastline. All stations recorded an abrupt and short-lived increase in wind-speed around 10 AM local time, indicating the passage of the gust front. Data courtesy the Israeli Meteorological Service.

Electrical Activity - More than 17,000 cloud-to-ground lightning strokes were registered by the ILDN during this event, exceeding the annual total amount of lightning strikes for the entire country (Figure 3b). As Figure 4 shows, at the peak of the event the average cloud-to-ground flash rates between 090-0930 LT were greater than 450 strokes per minute. One should consider that this is only the Cloud-to-Ground (CG) flash rate as the ILDN does not record Intracloud flashes (IC). If we accept the ratio of IC/CG~2 reported by Yair et al. (1998), then the total flash rate would be more than 1000 flashes per minute, exceeding the maximum global record of flash rates found in the Argentina-Paraguay border (Zipser et al., 2006).

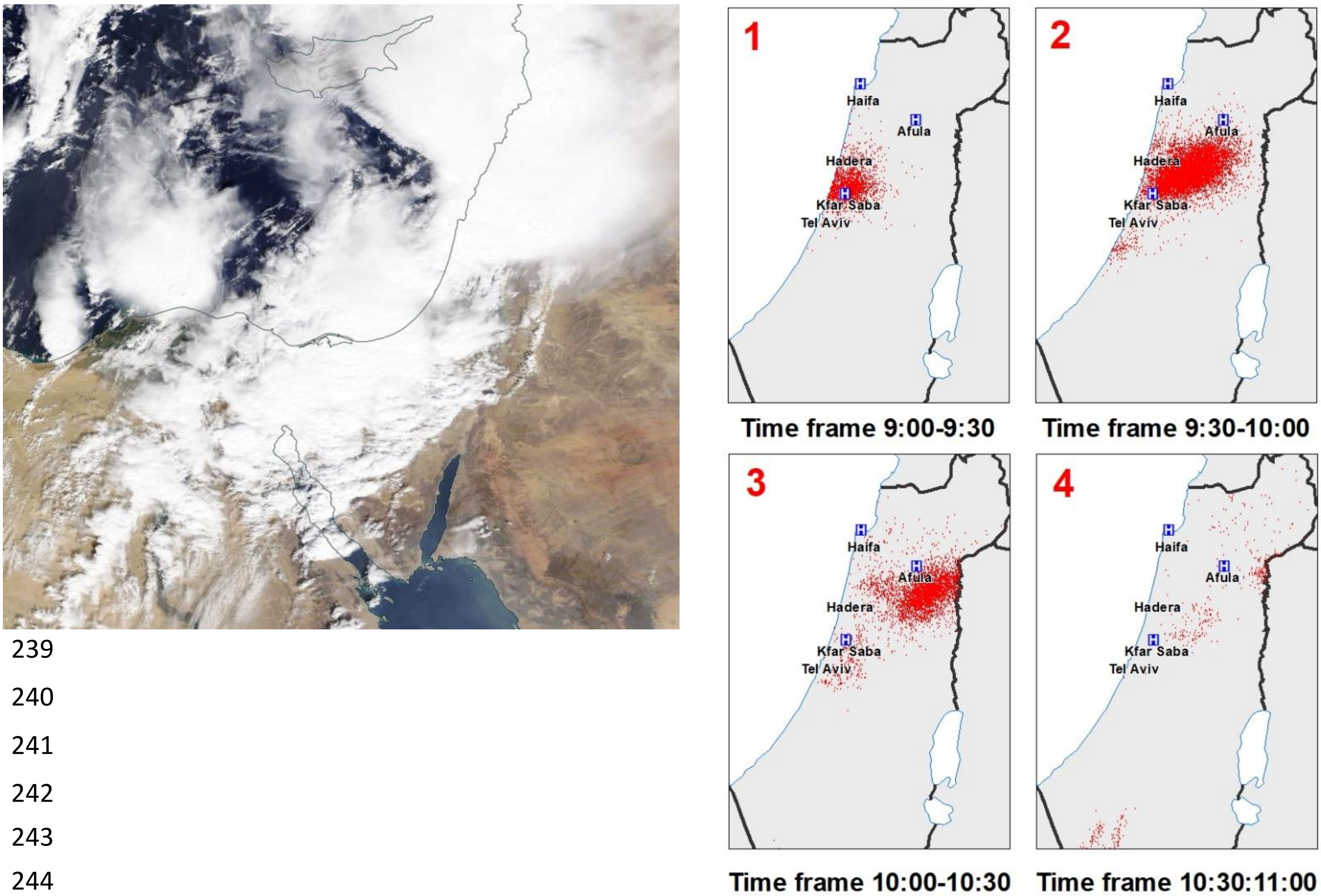

Figure 3: (left) Visible MODIS Satellite image at 12 UT when the cold front and thunderstorms already moved into Israel (right) Lightning strokes detected on October 25th 2015 by the ILDN (Israel Lightning Detection Network) operated by the Israeli Electrical Corporation. Each point is a ground stroke. The panels show cumulative values at 30 minutes intervals, local time indicated and the location of the 3 hospitals involved in this research.

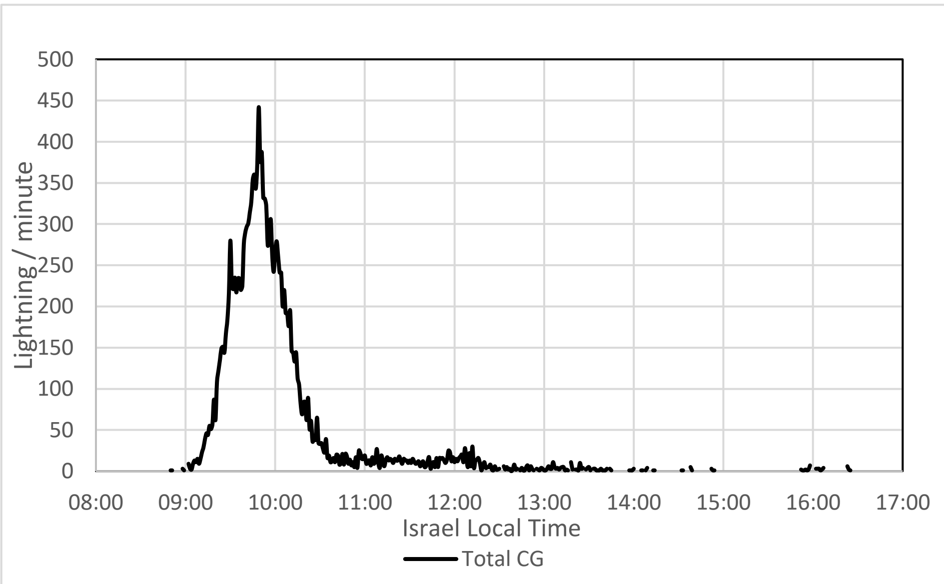

Figure 4: 1-minute accumulated lightning numbers detected on October 25th 2015 as a function of local time. The total cloud-to-ground stroke rate exhibits a sharp maximum around 09:45 local time, as the cells passed over central Israel.

4. Particle Concentrations

The results from the Israeli Ministry for Environmental Protection's air-quality monitoring network show a remarkable increase in the concentrations of PM 2.5 particles, up to 10-fold the normal values (Figure 5). This is due to the very strong winds ahead of the cells, that picked up considerable amounts of dust, pollen and other types of aerosols from the surface.

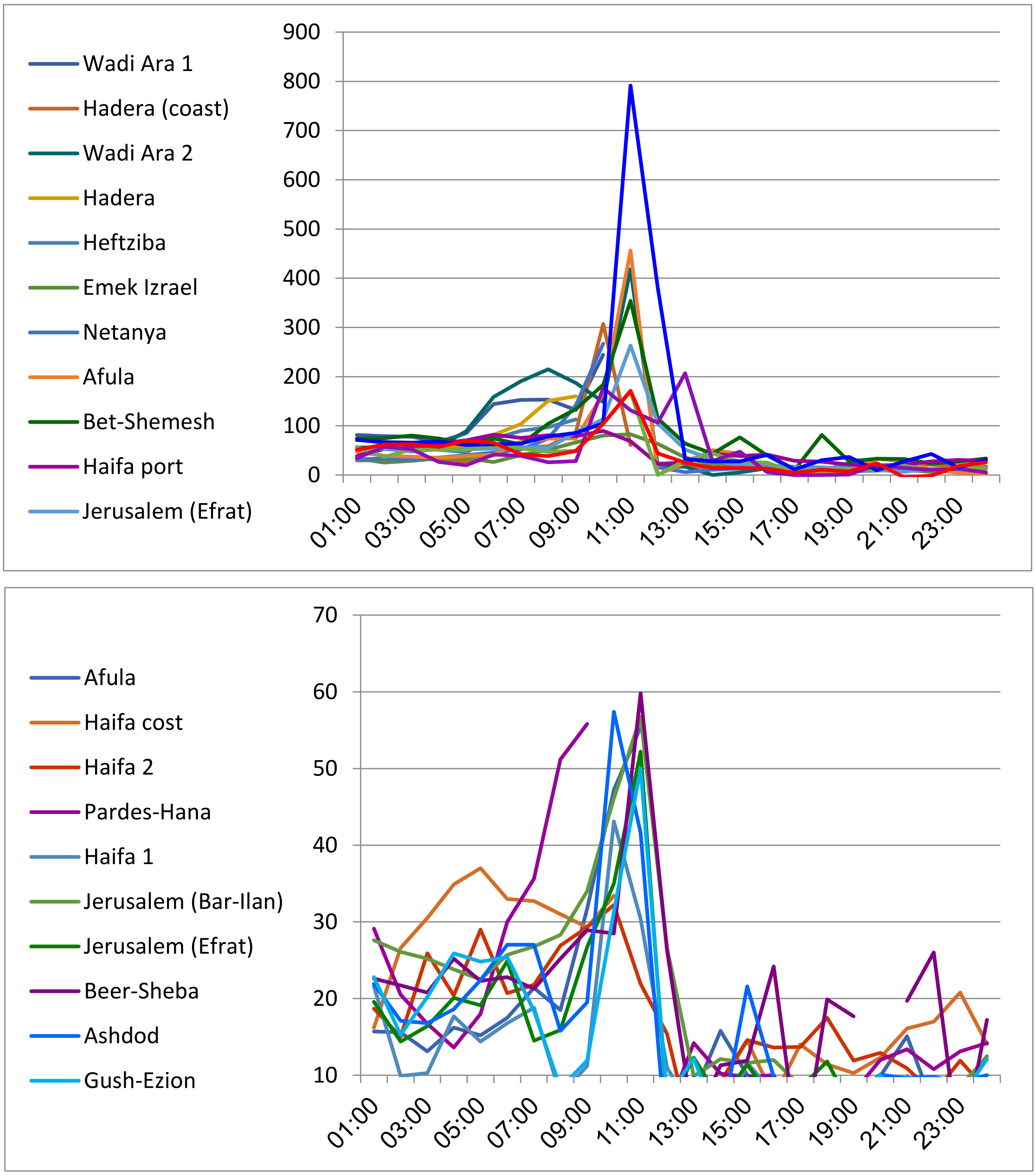

Figure 5: (a) Mass concentration of PM10 aerosols for several stations in central Israel, 25th October 2015. Data is given in µg m^{-3}. Note the peak around 1100 local time, coinciding with the passage of the gust front. The sharp, strong peak was meaured at the Rambam Medical Center in haifa. (b) The same as in (a), for PM2.5 aerosol concentrations.

The daily pollen amounts for October 2015 (Figure 6) exhibit two significant peaks, which are related to severe weather events. It should be noted that before the onset of the storm on October 25th, there were already larger than usual amounts of pollen and spores in the air (up be a factor of 3). This supports the thunderstorm asthma hypothesis of pollen processing inside the storm by humidity and electric fields, that results in rupture and release of allergens into the cold outflow (D'Amatto et al., 2015; Beggs, 2017). The decrease in pollen concentrations after the storm is explained by washout and dilution after the rain and winds associated with passage of the active cells. The list of flowering allergenic plants in October in Israel is presented in Appendix A.

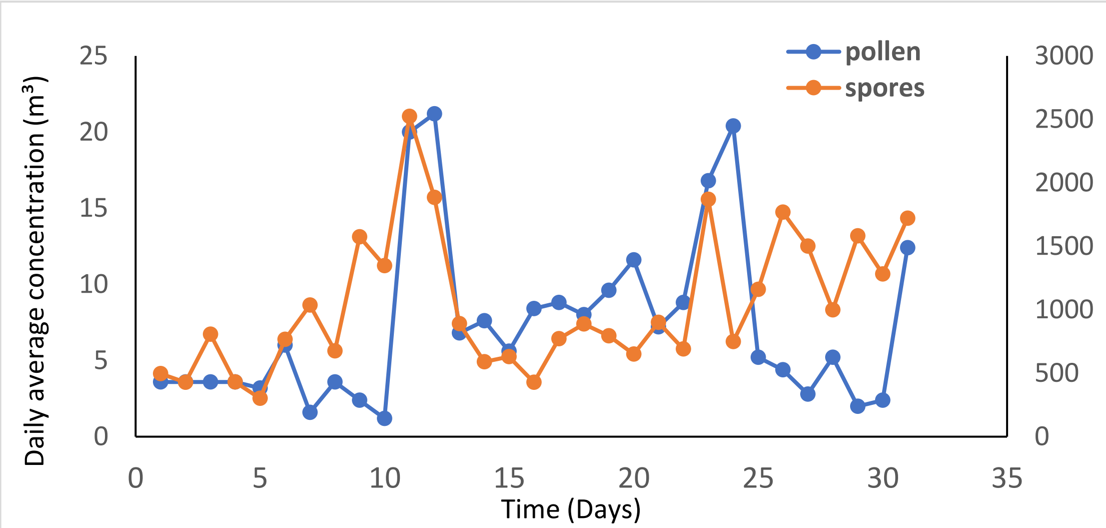

Figure 6: Daily average concentrations of pollen and spore numbers for October 2015, based on data collected at Tel-Aviv University's monitoring station in the botanical gardens on campus (Data courtesy of Prof. Amram Eshel, the Laboratory for Pollen Monitoring, Tel-Aviv University).

5. Hospital ER presentations

The hospital presentation records of patients with respiratory problems were obtained from three Israeli hospitals. The Meir Medical Center is located in the city of Kfar-Saba (population 110,000), 15 km north-east of Tel-Aviv in the central coastal plain. The Ha'Emek Medical Center is located in the city of Afula (population 43,000), a regional urban center located in an agricultural and rural part of northern Israel, close to Mt. Tabor. The Rambam Medical Center is located in Israel's largest port city of Haifa (population 280,000) and is the largest of the three. Figure 7 shows the records of a full week with numbers of patients, starting 3 days before the event. The ER presentation records show that the numbers of presentations of patients on October 25th increased compared with the numbers of the days before the storm. Although in absolute numbers the numbers may seem low, the values admitted on the day of the thunderstorm represent a clear deviation from monthly average for October. At the Meir (located just below the ground-track of the storm cells) and Rambam (located west of the ground-track) hospitals there was a clear increase in the number of ER presentations which can be related to the passage of the gust-front in the surrounding areas and the ensuing increase in particle concentrations. Based on records of arrival times at the ER, we noted that within several hours after the thunderstorm there was a noticeable increase in the number of patients with respiratory problems of a specific nature (a list of diagnoses only related to asthma and allergic respiratory diseases), in line with the pattern reported by Newson et al. (1997) and Thien et al. (2018). At the Ha'Emek medical center in Afula there was no significant increase and the numbers were practically the same as the day before. In all three hospitals, this increase in patient presentation to the ER with respiratory problems persisted for 24 hours and a clear decline was noticed in the following day, likely related to a wash-out effect by precipitation that followed the passage of the active cells. This decline was more pronounced at the Meir and Ha'Emek hospitals which experienced heavy rains during of the storm, lasting for 48 hours. At the Rambam Medical Center in Haifa the numbers of ER presentations with respiratory problems rose again to high values, likely due to the ambient values of air pollution related to aerosols in the Bay of Haifa, a well-known source of industrial emissions (Sa'aroni et al., 2018).

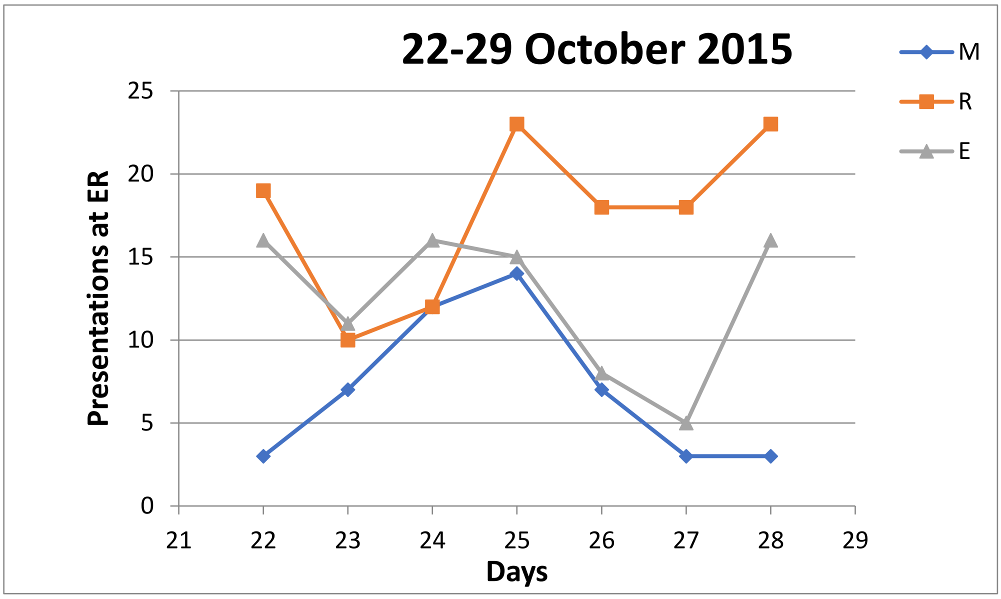

Figure 7: Emergency room presentations at 3 Israeli hospitals in the 3 days preceding and following the October 25th 2015 super-cell event: M = Meir Medical center (blue), R = Rambam medical center (orange), E = HaEmek medical center (grey).

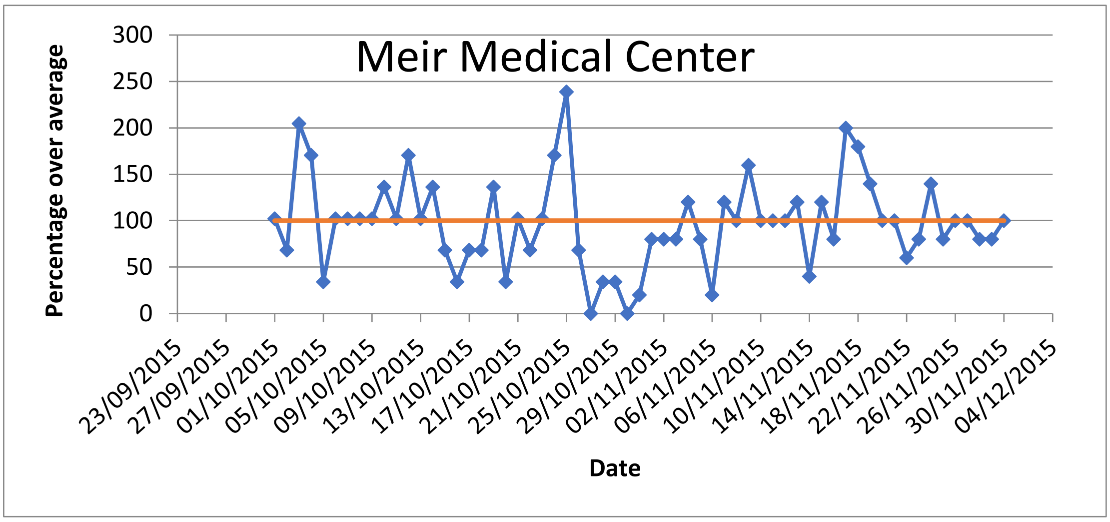

Figure 8: Two months of ER presentations of patients with respiratory problems at the Meir Medical Center in Kfar-Saba, central Israel (for the period 1.10.2015-30.11.2015). The October 25th record shows a 250% increase above the long-term average in a single day.

6. Discussion

In most reported cases of thunderstorm asthma in Europe, Canada, US and Australia, the initiating agents were spring or summer convective storms, and their occurrence coincided with the flowering season of many plant species whose pollen is known to be highly allergenic. In Israel, thunderstorms and lightning occurs mainly during winter months ((December-January-February) and are associated with the passage of Cyprus Lows or Red-Sea Trough [RST] (Ziv et al., 2008; Shalev et al., 2011;

Yair et al., 2014; Ben-Ami et al., 2015). During these months there is little flowering and pollen concentrations are low (Keinan, 1992). However, some of the most severe convective events in Israel occur during fall and spring months, when the RST pressure system transports mid-level moisture into the eastern Mediterranean and the atmosphere is unstable, enabling deep convection and intense lightning activity. These events occur mostly in October-November and March-May, and coincide with flowering of various allergen-bearing plant species, for example *Ambrosia* spp. (Waisel et al., 1997; Waisel et al., 2008; Appendix A), and so have the potential to instigate thunderstorm-asthma epidemics.

The October 25th 2015 super-cell event was by far one of the strongest thunderstorm episodes ever recorded in Israel. The unique synoptic circumstances of this event coincided with massive flowering of *Ambrosia* spp. already shown to be highly allergenic and wide-spread in central Israel (Yair et al., 2017; 2018). Previous studies suggested that the mechanism by which thunderstorm dynamics recycle ambient aerosols is very effective in releasing allergens from pollen particles, that may otherwise not reach and affect sensitized populations (Taylor and Jonsson, 2004; D'Amato et al., 2015). The strong electric fields that existed during that thunderstorm, manifested by the high flash rate, as well as the high humidity and presence of rain, likely aided in rupturing the pollen membranes and enriching the air with respirable allergens, that accompanied other aerosol particles already present in the environment. The track of the storm passed directly above the densely populated, mostly urban part of Israel, where the ambient concentrations of pollution particles was already high. Additionally, as the spore counts indicate (Figure 6), the background levels of fungal spores, that may play an important role in triggering allergenic asthma (Packe and Ayers, 1986; Dales et al., 2003), was high the day before the storm. Thus, it was the convergence of several factors on the particular day that initiated the observed increase in ER respiratory presentations. Admittedly, the public health data presented in this study is limited, but follow-up research being presently conducted will help us to understand the characteristics of admitted patients (as performed by Thien et al., 2018).

What can be done to protect sensitized populations against thunderstorm asthma, especially in light of the emerging trends of thunderstorm frequency (Romps et al., 2016; Brooks, 2013; Diffenbaugh et al., 2013; Yair et al., 2018), the extended period of plant flowering (Ziska et al., 2011) and the increase in allergen content in pollen (Singer et al., 2005) in a warmer climate? A thorough review published by the

World Allergy Organization (D'Amato et al., 2015) surveyed the expected changes in the occurrence of thunderstorm asthma and concluded that people with hypersensitivity to pollen allergy should be advised to stay indoors when there are clear indications that thunderstorm activity is expected. Silver et al. (2018) examined the seasonality and predictability of asthma-related presentation at Melbourne hospitals, using time-series ecological approach. They suggest that the observed spring peak in asthma patient numbers may be related to thunderstorm asthma as they are associated with rainfall, high humidity, and enhanced grass pollen levels, but the rarity of such events undermines predictive capabilities. Indeed, early-warning capabilities for lightning are becoming operational in some countries (for example the Lightning Potential Index [LPI] calculated from the microphysical fields of numerical models such as the WRF and which is being used for medium-range weather forecast models (Lynn and Yair, 2010; Lynn et al., 2012) and pollen forecast models are also used to predict the onset and spread of pollen concentrations (Sofiev et al., 2013; Zhang et al., 2014). However, there seems to be a gap between a combined forecasting procedure of pollen and lightning and administrating public-health warnings, and thus sensitive populations may not be effectively alerted. We therefore suggest to include proper public health alerts when there is clear indication for the coincidence of thunderstorms during plant flowering season in specific regions where allergenic species are found.

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& - E. Shachar and M. Rotem contributed equally to this work.

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Figure Captions

Figure 1: A schematic description of the mechanism that enhances the concentrations of airborne aerosols (either pollution particles or pollen) ahead of a mature thunderstorm (Taylor and Jonsson, 2004).

Figure 2: Wind speed at 4 different stations along Israel. Bet Dagan (in blue) is located 12 km southeast of Tel-Aviv. Hadera Port (red) is located on the coastline, 45 km north of Tel-Aviv. Hakfar Hayarok (green) is 5 km northeast of Tel-Aviv, and Tel-Aviv coast (purple) is located on the Mediterranean coastline. All stations recorded an abrupt and short-lived increase in wind-speed around 10 AM local time, indicating the passage of the gust front. Data courtesy the Israeli Meteorological Service.

Figure 3: (left) Visible MODIS Satellite image at 12 UT when the cold front and thunderstorms already moved into Israel (right)Lightning strokes detected on October 25^{th} 2015 by the ILDN (Israel Lightning Detection Network) operated by the Israeli Electrical Corporation. Each point is a ground stroke. The panels show cumulative values at 30 minutes intervals, local time indicated and the location of the 3 hospitals involved in this research.

Figure 4: 1-minute accumulated lightning numbers detected on October 25^{th} 2015 as a function of time. The total cloud-to-ground stroke rate (grey) exhibits a sharp maximum around 09:45 local time, as the cells passed over central Israel.

Figure 5: Mass concentration of PM10 aerosols for 16 stations in Israel, 25^{th} October 2015. Data is given in µg m^{-3}. Note the peak around 1000 local time, coinciding with the passage of the gust front. The sharp, strong peak was meaured at the Rambam Medical Center in haifa.

Figure 6: Daily average concentrations of pollen and spore numbers for October 2015, based on data collected at Tel-Aviv University's monitoring station in the botanical gardens on campus (Data courtesy of Prof. Amram Eshel, the Laboratory for Pollen Monitoring, Tel-Aviv University).

Figure 7: Emergency room presentations at 3 Israeli hospitals in the 3 days preceding and following the October 25^{th} 2015 super-cell event: Meir Medical center (blue), Rambam medical center (orange), HaEmek medical center (grey).

Figure 8: Two months of ER presentations of patients with respiratory problems at the Meir Medical Center in Kfar-Saba, central Israel (for the period 1.10.2015-30.11.2015). The October 25^{th} record shows a 250% increase in a single day.

Appendix A

Table showing flowering months for various allergenic plants in Israel (based on Keinan, 1992). Yellow marks little flowering, dark brown marks massive flowering.

	1	2	3	4	5	6	7	8	9	10	11	12
Cynodon dactylon												
Hyparrhenia hirta												
Pennisetum clandestinum												
Stenotaphrum secundatum												
Paspalum vaginatum												
Zoisia sp.												
Sorghum halepense												
Chloris gayana												
Poa sp.												
Hordeum sp.												
Lolium sp.												
Bromus sp.												
Dactylis glomerata												
Avena sp.												
Parietaria sp.												
Ricinus communis												
Chenopodium sp.												
Urtica sp.												
Mercurialis annua												
Plantago sp.												
Amaranthus sp.												
Inula viscosa												
Ambrosia sp.												
Xanthium sp.												
Salsola kali												
Atriplex halimus												
Artemisia monosperma												
Artemisia herba alba												
Eucalyptus sp.												
Thuja sp.												
Cupressaceae												
Phoenix dactylifera												
Quercus ithaburensis												
Quercus calliprinos												
Pistacia lentiscus												
Pistacia palaestina												
Olea europaea												
Acacia sp.												
Carya illinoinensis												
Ailanthus glandulosa												
Ceratonia siliqua												
Schinus sp.												
Casuarina sp.												