Author's Response:

We thank both referees for acknowledging the significant changes done in the manuscript following their previous comments. We most appreciate the suggestion given in the scope of "minor changes" to better improve the manuscript. A point to point response to each referee is given below.

Sincerely,
Leenes Uzan, Dr. Smadar Egert and Prof. Pinhas Alpert

Authors' response to referee #1:

Referee comment:
Abstract: From the title one would expect that ceilometers provide the main contribution to the study. This is not reflected in the abstract anymore. Please highlight the role of ceilometers more clearly.
Author's response: Comment accepted.
Author's changes in manuscript: We changed the title and the abstract accordingly.

Referee comment:
Introduction: In general the authors followed the recommendations of the reviewers. However: check the "Stavros/Solomos"-problem (throughout the text; Stavros is the first name, so use Solomos!). Include a short section on the radiative forcing because this has now been covered in the results-section (as mentioned by reviewer #2 there are several papers in Tellus B special issues of 2009 and 2011). In my view the introduction is now sort of long. Certainly, the extension was triggered by trying to fulfill the requirements of review #2. Anyway, check if there is potential to slightly shorten it.
Author's response: Comments accepted.
Author's changes in manuscript: Stavros was changed to Solomos. Reference to radiative heating was added to the "Results and discussion" section. The introduction was slightly shortened.

Referee comment:
Ceilometer section: Include the statement of the limited measurement range more clearly – this was the major criticism of reviewer #2 (and also raised by me) – after (e.g.) line 286. This is indeed mandatory, and is independent on the problems discussed before (overlap, cosmetic shift, etc.): it is an effect of signal attenuation due to reduced atmospheric transmission and happens to all lidar systems (think

about a dense cumulus cloud for example – the same effect). Thus, add 1-2 sentences here and refer to them later in the manuscript whenever necessary.

Author's response: Comments accepted.

Author's changes in manuscript: We added sentences referring to the limitations of ceilometers under dense conditions in the "ceilometers" subsection 2.1.

Referee comment:

Ceilometer section: Line 246: Note that the statement in the Vaisala user's guide on the output does not fulfil strict scientific standards: "two-way attenuated backscatter profile with sensitivity normalized units (100000 srad km)−1" is not a physical quantity. These numbers are not the correct definition of attenuated backscatter (see β ∗ in one of the cited Wiegner-papers and the explanations of reviewer #2) as it requires a calibration. Just state in the paper, that the range corrected signal (in arbitrary units) is stored (even this is not necessarily true if the h2-parameter is not set – this is fortunately not relevant for the lowest 2.4 km) and replace all cases of "attenuated backscatter". By the way: the authors correctly mentioned in line 264 that the "real" attenuated backscatter cannot be derived.

Author's response: Comments accepted.

Author's changes in manuscript: We added the following text in "Ceilometers" subsection .2.1: "The internal calibration applied to convert the signal count output to “attenuated backscatter” does not always fully represent the actual lidar constant, therefore, it is not accurate enough for meteorological research. Hence, in this study we defined the ceilometer profiles as range corrected signal profiles in arbitrary units". We changed the "attenuated backscatter profiles" produced in this research to range corrected signal profiles (in a.u.).

Referee comment:

Ceilometer section: Final comment (to lines 265ff, "Nevertheless..."): what is the purpose of these sentences: Rayleigh calibration is not possible, or Rayleigh requires averaging over 4 hours? Cloud calibration (see O'Connor et al., 2004) should be used? What is really meant with "background correction"?

Author's response: Comments accepted.

Author's changes in manuscript: We changed the text to make it clearer.

Referee comment:

Ceilometer section: Please reconsider my suggestions of the use of the (already listed) citations; they were not properly included. Ansmann et al. (2011) and Papayannis et al. (2008) are not covering ceilometers (but the benefit of lidars for dust observations in general), so these citations do not fit to lines 230–232 in V3. The statement on the water vapour absorption should be more precise (lines 276–278 of V3), maybe something like: "... water vapour distribution has a small effect on *the pronounced change of the signal shape at the top of the mixed layer or at boundaries of an elevated aerosol layer (Wiegner and Gasteiger, 2015)". The citation of Mona et al. (2012) is missing in the text.*

Author's response: Comments accepted.

Author's changes in manuscript: We relocated the citation and added the Mona et al. (2012) citation that was unfortunately neglected.

Referee comment:

Results section: In context of Fig. 17 the authors refer to "attenuated backscatter". Either this should be changed to something like "range corrected signal with the Vaisala's inherent normalization" or better just "range corrected signal (in arbitrary units)". If the ceilometer's sensitivity remains constant during the event (which is likely) and the effect of changing water vapor absorption is neglected, even uncalibrated signals at a given site can be compared, i.e., discussion of the temporal evolution of the dust at that site is feasible and provides a useful contribution to the paper.

Author's response: Comments accepted.

Author's changes in manuscript: The units in Fig. 17 were changed to range corrected signal profiles in a.u.

Referee comment:

Results section: In view of the title of the paper I suggest to extend a little bit the discussion of the ceilometer data: As the MLH cannot be derived from the ceilometer data when the (strong) decrease of the transmission overcompensates the large backscatter coefficients of the dust, at least statements like "dust was present up to at least a height of xxx m" can be made. CALIOP data indicate that the top of the dust layer was typically between 2 and 4 km, however quite variable (in time and space) and sometimes multi-layered. Because of lack of co-located measurements (except the example shown in the revised paper, where some, but not all, ceilometer sites are met) no independent measurements of the actual distribution of the dust are available. Thus, the interpretation of the (upper part of the) ceilometer profiles must remain ambiguous. This can be discussed in the paper. However, when describing the lower boundary of the dust layer, the authors can rely on the ceilometer data (as they do in the revised version).

Author's response: Comments accepted.

Author's changes in manuscript: The ceilometer contribution in the lower part of the atmosphere was better emphasized in the results section.

Referee comment:

Results section: Line 571: What is meant with a ”two-layer shape”? An elevated layer? Similar problem at line 618 (”arc shape ascent”).

Author's response: We referred to the ununiformed dust layer visible by the ceilometers' plots as two separate layers (descending down to 500 m ASL and rising from ground level). The "arc-shape" was referred to the thin dust layer formed aloft in the shoreline ceilometers following the entrance of the sea breeze front.

Author's changes in manuscript: We rephrased "two-layer shape" to " an ununiformed dust layer" and "arc-shape " to "a narrow dust layer".

Referee comment:

Results section: Fig. 17: It seems that the height above sea level is shown, not the height above ground level as indicated by the y-axis. The figure caption seems to be okay.

Author's response: Comment accepted.

Author's changes in manuscript: The y-axis was corrected height ASL.

Referee comment:

Results section: Fig. 21: Give wavelength of the CALIOP-data. A blow-up is advisable to better see the situation over Israel. Comment on the ”blue range” below 2 km: is this total attenuation? What is the elevation of the ground? What is the green line in the right panel showing?

Author's response: We commented in line 627: "We assume the CALIOP lidar did not produce data beneath 2 km ASL due to total attenuation."

The green line indicates the overpass on 6 September 2015 referred by previous studies showing the distance from Israel. It is omitted in the updated CALIPSO plots.

Author's changes in manuscript: We focused the CALIPSO plots on the data produced above Israel. We addressed ground elevation height and mentioned the CALIOP wavelength (532 nm) in the caption of Fig. 21.

Referee comment:

Conclusions: A general message to remember is missing: I suggest to clearly point out the contribution, the strengths, and the limitations of the ceilometer network when observing dust storms (not necessarily as strong as this event). In the paper they was demonstrated for one very strong event, but conclusions that are beneficial for future investigations and (maybe) can be used for other regions should be made.

Author's response: *Comments accepted.*

Author's changes in manuscript: We have changed the conclusions section accordingly.

Referee comment:
Miscellaneous: refer to Fig. 20 instead of Table 6 in line 355. Change "uncelebrated" to "uncalibrated" in line 281, captions of Figs. 6-13 should be changed to 7.-10. September.
Author's response: Comments Accepted.
Author's changes in manuscript: Corrections were made accordingly.

Author's' response to referee #2:

Referee comment:
P13, L355: Global radiation measured … Table 6. …. ? In Table 6, I find PM10 for 31 stations only. Do you mean Table 7 (but I do not have Table 7?)
Author's response: Mistake. The reference is Fig. 20
Author's changes in manuscript: The reference was changed from Table 6 to Fig. 20.

Referee comment:
P13, L378: I have generally my problems with the uncertainty statements (here MSG, somewhere else MODIS). I think in the paper of Mamouri they compared MODIS with AERONET for these very large AODs and gave some uncertainty statements. At least, 15% uncertainty appears to me rather low… for these extreme dust conditions with AOD probably even larger than 3… , I think the AOD uncertainty is of the order of 1.0 or even more.
P14, L395: Again, an uncertainty of 0.1 is probably ok for AOD< 1.0, but what about cases with >2.5? Then the error is certainly much larger, of the order of 0.5 to 1.0.
Author's response: We did not find explicit estimation of the MSG SEVIRI AOD uncertainty during high AOD values except for a general remark based on a comparison done between SEVIRI AOD and AERONET AOD in the scope of EUMETSAT Scientific Validation Report SEVIRI Aerosol Optical Depth (23 Oct 2017) *:" For very high AOD conditions (>1.5) a negative bias is observed".* Similar conclusions were found for MODIS AOD. We wish to thank Dr. Yevgeny Derimian from the university of Lille for data and personal correspondence on this issue.
Author's changes in manuscript: We added comments of increased uncertainty under high AODs (>1.5).

Referee comment:
Section 3, I would introduce subsections! … with head lines (titles): 3.1 7 September 2015, 3.2 8 September 2015 etc. That would make the full and very complex discussion section easier to read.
P15, L426: Now the ceilometer observations are introduced….
Author's response: Comment accepted.
Author's changes in manuscript: We added subsection by dates as recommended.

Referee comment:
P10, L286: you state: …. we refer to the ceilometer signal count profiles between 100-1000m. This statement is good, but I am afraid that non-lidar dust-interested readers will not remember that statement when they see Figures 6-12. I will come to this point again, below.
P23, L557: .. and now, the discussion of the 8 September starts. As mentioned above, we need a clear statement that the colored areas in Figs 6-12 only show the lowest few hundred meters of the dust layer (which actually reached up to 4-5 km according to all the articles published before: Mamouri, Solomos, Gasch, and all the CALIOP observations, including the one shown in Fig 21, and Fig.21 comes much too late, to my opinion). Without such a clear remark (and this remark is definitely not given), most readers will intuitively think, the ceilometers show the entire dust layer.
P24, L590: … which may indicate the dust plume base height….. Again this statement is confusing when having the colored areas observed with ceilometers in mind, which suggest--- TOP HEIGHT. Non-lidar people will not understand what you want to say… without these explanations I suggested above.
Author's response: The "Results and discussion" section is arranged by dates starting from 8 September 2015 to 10 September. The CALIOP observations refer to10 September therefore they were mentioned last.
Author's changes in manuscript: We added a short paragraph in the "Results and discussion" section clarifying the colours of the ceilometers' plots in context of the ceilometers' measurement limitations.

Referee comment:
If I compare Fig 9 with Fig 16 (the radiosonde profiles are very nice now!), then my opinion is confirmed that the ceilometers see only the lowest few hundred meters of the dust layer because the top height of the colored ceilometer backscatter areas coincide with the temperature inversion height (the base of the main dust layer, higher up…).
Author's response: Agreed.
Author's changes in manuscript: No change.

Referee comment:

Fig 13: This plots shows nothing? Clear skies? Or just overloaded by heavy dust? The plot is almost entirely deep blue! But there should be a lot of dust according to all the satellite observations presented. So, maybe an APD, PMT overloading effect. The ceilometer detectors were just overloaded because of the huge amount of dust around? Please clarify.

Author's response: The deep blue scale evident in all Mount Meron ceilometer plots (Fig. 13) indicate total attenuation distinctively from 7 September ~ 14 UTC to 8 September ~ 16 UTC. Due to the complexity of the dust plume progress and the weak signal counts shown up to 3.5 km ASL (before 7 September ~ 14 UTC and after 8 September ~ 16 UTC), the assumption of a total attenuation throughout the period analysed is uncertain. Unfortunately, we did not have auxiliary measurements from the Mount Meron region to justify our assumptions.

Author's changes in manuscript: We added the aforementioned assumption in the manuscript.

Referee comment:

Fig 17: Now the quantitative analysis is much improved. But I want to say, just that you think about it…..: An attenuated backscatter coefficient of 10-4 m-1 sr-1 is equivalent to 4 km-1 extinction coefficient (for a lidar ratio of 40sr), and thus 2x10-4 means 8 km-1 extinction. Do you have the feeling, this is correct? I just ask you! Do you believe in your numbers?

Author's response: Unfortunately Israel does not poses a calibrated lidar capable of true extinction measurements. However, previous study of the dust event in Cyprus by Raman lidar (Mamouri et al., 2016) provided extinction coefficient with similar order of magnitude. Based on the CL31 manual the ceilometer is capable to measure visibility values in clouds in the range of 15-150 m (dust visibility was estimation by IMS observers to be ~ 200 m) and hence, measurement capabilities within this range.

Author's changes in manuscript: No change.

Referee comment:

The other point: Fig 17 nicely shows that backscatter signals (from five of the seven ceilometers) which are backscattered from heights above 500-700m were completely attenuated so that the attenuated backscatter coefficient is simply zero. That does not mean that the backscatter coefficient was zero…… The backscatter coefficient was probably even larger than at ground. So, attenuated backscatter is a very 'dangerous' parameter.

Author's response: The attenuated backscatter profiles are the ones available from the ceilometers. Nevertheless, following the referees' recommendations and changed the "attenuated backscatter" units to " range corrected signal profiles (in a.u.)".

Author's changes in manuscript: "Attenuated backscatter" units were changed to " range corrected signal profiles in a.u. ".

Referee comment:

P23, L571: … reveal a two-layer shape …. How do you know, there may have been even 4 or 5 distinct layers up to 4-5 km height.

Author's response: We referred to the layers visible by the ceilometers (below ~ 1 km).

Author's changes in manuscript: We rephrased "two-layer shape" to " an ununiformed dust layer"

Referee comment:

Fig.20: Black numbers on dark blue or dark brownish background… any idea to improve that?

Author's response: Comment accepted.

Author's changes in manuscript: We changed the color of the numbers in figures 19-20 from black to white where the background was dark.

Referee comment:

P26, L625: The dust top height of 2-4 km is mentioned here for the first time (if I read the paper carefully enough). This is simply much too late. And the overall context given by the papers of Mamouri et al., Solomos et al. (presenting CALIOP obs.), Gasch et al. (also presenting CALIOP obs.) clearly shows that the top height was always and everywhere at 4-5km height, in full agreement with your Fig 21 for 10 September. So, please improve…. Not 2-4 km, it was 4-5 km …

Author's response: Comments accepted.

Author's changes in manuscript: We rephrased the sentence to " ...a dust layer up to 5 km ASL".

A list of relevant changes made in the manuscript:

1. Updated abstract
2. The introduction was shortened (Sect. 1)
3. The structure of "Results and discussion" section was changed.
4. The "Conclusions" section was broadened.
5. Several figures' presentation, unites and axis were changed.

New insights into the vertical structure of the September 2015 dust storm employing 8 ceilometers and auxiliary measurements over Israel

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Abstract

On 7 September 2015 an unprecedented and unexceptional extreme dust storm struck the Eastern Mediterranean (EM) basin. Here, we provide an overview of the previous studies and describe the dust plume evolution over a relatively small area, i.e., Israel. This study ~~employs~~presents vertical profiles provided by an array of 8 ceilometers covering Israeli shore, inland and mountain regions. We employ multiple tools including~~ an array of eight ceilometers,~~ spectral radiometers (AERONET), ground particulate matter concentrations, satellite images, global/diffuse/direct solar radiation measurements and radiosonde profiles. Main findings reveal that the dust plume penetrated Israel on the 7 September from the northeast in a downward motion to southwest. On 8 September, the lower level of the dust plume reached 200 m above ground level, generating aerosol optical depth ~~of~~ (AOD~~>~~) above 3, and extreme ground particulate matter ~~concentration measured on ground level~~concentrations up to ~10,000 μm m^{-3}. A most interesting feature on 8 September was the very high variability in the surface solar radiation in the range of 200-600 W m^{-2} (22 sites) over just a distance of several hundred km in spite of the thick dust layer above. Furthermore, 8 September shows the lowest radiation levels for this event. On the following day, ~~9 September,~~ the surface solar radiation increased, thus enabling a late ~~(~~~(between 11-12 UTC) sea breeze development mainly in the coastal zone ~~along with 5 m s^{-1} surface winds~~ associated with ~~arc-shaped~~a creation of a narrow dust ~~layers.~~layer detached from the ground. On 10 September the AOD values started to drop down to ~ 1.5, the surface concentrations of particulate matter decreased as well as the ceilometers aerosol indications~~; Still, as indicated by~~ (signal counts) although CALIPSO ~~a 2-4 km~~revealed an upper dust layer remained.

1. Introduction

An exceptionally extreme dust storm prevailed over the Eastern Mediterranean (EM) on September 2015. The Israeli meteorological service (IMS) declared the dust storm to be extraordinary as it occurred on early September (7-10 September), extended over a time span of 100 hours creating extreme ground level particulate matter (PM) concentrations (e.g. 100 times above the hourly average of PM10 in Jerusalem). On 7 September, prior to the penetration of the dust storm over Israel, IMS reported ~~(http://www.ims.gov.il/IMS/CLIMATE;~~(http://www.ims.gov.il/IMS/CLIMATE; in Hebrew) a heat wave~~ which prevailed~~ over Israel causing harsh weather conditions of 80-90% relative humidity, 42 °C in valleys, 38 °C in mountains. On 8 September, visibility decreased below 3 km and consequently, inland aviation was prohibited until ~~the~~ 9 September (Fig.1). Concurrently, severe ground level PM concentrations resulted with a public warning from outdoor activities~~,~~ issued by the environmental protection ministry. Finally, on 11 September, as visibility increased, the IMS confirmed the dust storm ended, whereas the heat wave was over ~~only~~ two days later, on 13 September, subsequent to a profound change in weather conditions. The PM concentrations declined to values measured prior to the dust storm ~~(http://www.svivaaqm.net/Default.rtl.aspx;~~(http://www.svivaaqm.net/Default.rtl.aspx; in Hebrew) only on 14 September, though the AERONET measurements (https://aeronet.gsfc.nasa.gov) stationed in central and southern Israel reveal that the aerosol optical depth (AOD) resumed to values prior to the dust storm only on 17 September.

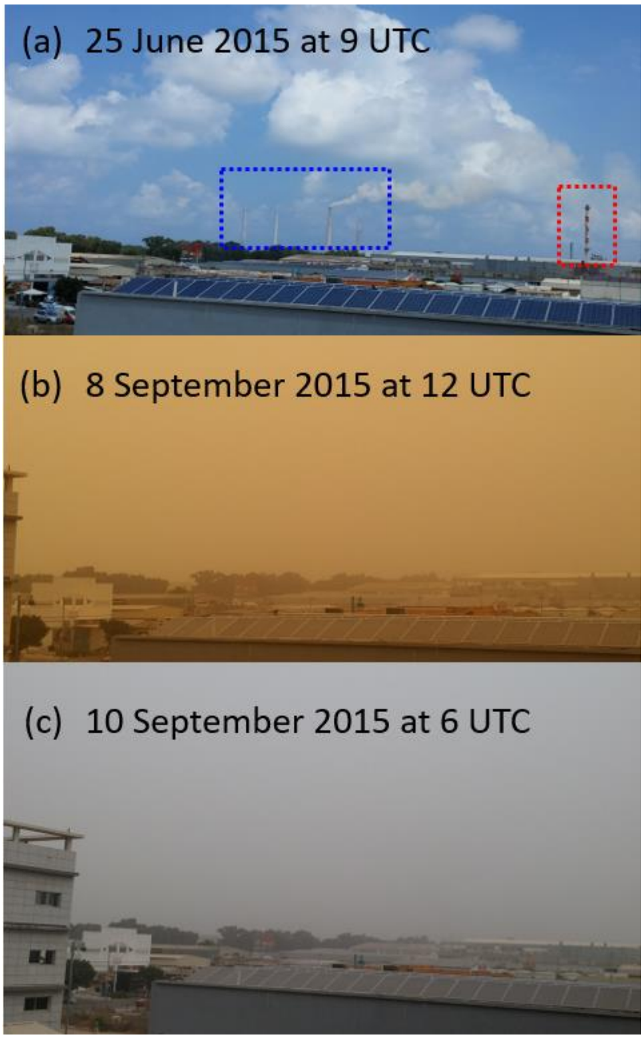


Figure 1. Photographs taken from the central coast of Israel, adjacent to the Hadera ceilometer, 3.5 km southeast to ~~the~~ stacks of a power plant (indicated by a blue rectangle) and 600 m north to a factory stack (indicated by a red rectangle). The photographs were taken prior to the dust storm, on 25 July 2015 (a~~)~~), and during the dust storm, on 8 September 2015 (b) and 10 September 2015 (c). Notice that ~~during the dust event (b,c)~~ the stacks ~~clearly seen in (~~that are visible on a~~) from the same spot,~~ clear day (a) are invisible~~.~~ during the dust storm (b, c).

Investigation of the mechanisms leading the severe dust storm was performed by Gasch et al. (2017) using a state of the art dust transport model ICOsahedral Nonhydrostatic (ICON) with the Aerosol and Reactive Trace gases (ART) (Rieger, et al., 2015). The model concentrated on the EM with one global domain (40 km grid spacing, and 90 vertical levels from 20 m to 75 km) and 4 nested grids (20, 10, 5 and 2.5 km grid spacing and 60 vertical levels from 20 m to 22.5 km). Simulations were done for three consecutive days from 6-8 September. Model results delineated an unusual early incidence of an active Red Sea Trough (Fig.2; Alpert et al, 2004) over Mesopotamia, followed by meso-scale convective systems over the Syrian-Iraqi border generating three cold-pool outflows. On the night between 5 and 6

September, a convective system fueled by an inflow along the eastern side of the Red Sea Trough, moved northeast over the Turkish-Syrian border region. The convective system intensified overnight and generated a first weak cold pool outflow on ~~the~~ 6 September. After sun rise, ~~as the nocturnal boundary layer dissipated, an increase of downward mixing lead to~~ an increase of surface wind speeds ~~consequently causing~~caused dust ~~to~~ pick up over Syria. ~~The high surface wind speeds sustained during the day due to a strong and shallow heat low whereas sea breeze transported dust to the south towards Jordan. At this point, the~~The atmospheric instability over the Syrian-Iraqi border created a second convective ~~cool~~cold pool outflow from the Zagros mountain range west into Syria. The gust from the second ~~cool~~cold pool outflow ignited a third ~~cool~~cold pool outflow at 20 UTC~~. The third outflow~~ which moved southerly along the eastern flank of the Red Sea Trough~~ and shifted warm and moist air masses along the way. Past midnight, on~~. On 7 September~~, the intensified third cool pool outflow shifted to the west. At~~ 10 UTC~~ 7 September~~, rainfall and an increase of surface wind speeds north-west of Syria strengthened the third ~~cool~~cold pool outflow~~. Consequently,~~ leading to transportation of enormous dust emissions ~~transported~~(up to 5 km) southwest~~ up to 5 km. The~~. By nightfall of 7 September, the aged second ~~cool~~cold pool ~~outbreak re-intensified~~outflow merged with the third cold pool outflow, over Jordan and southwestern Syria~~ and merged with the third outflow with the nightfall of 7 September.~~. After midnight, ~~on~~between 7 and 8 September, the dust transported over Israel~~ and was mostly influenced by local circulation systems in the EM~~. Model simulations were compared to in-situ measurements and satellite images: visible electromagnetic spectrum from Moderate Resolution Imaging Spectroradiometer (MODIS: https://modis.gsfc.nasa.gov/) aboard the Aqua satellite; AOD from the Terra satellite; RGB dust product from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) upon the Meteosat Second Generation (MSG) satellite; ~~total~~Total attenuated backscatter from Cloud-Aerosol Lidar upon the Infrared Pathfinder Satellite Observations (CALIPSO: https://www-calipso.larc.nasa.gov/). ~~Ground~~Investigation over Israel employed measurements from ground level meteorological ~~measurements~~stations (3 sites) and PM ~~concentration~~measurements (3 sites~~) in Israel were employed.~~). Results revealed the model lacked sufficient development of a super critical flow, which in effect produced the excessive surface wind speeds. Eventually, this misled the forecast of the dust advection southwest into Israel.

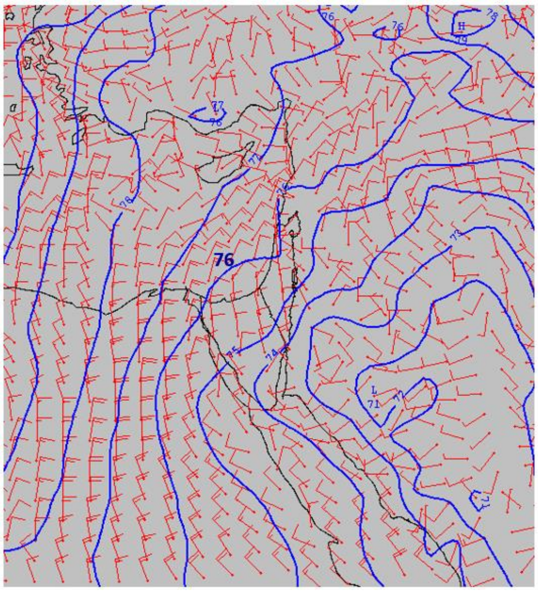


Figure 2. 925 mb map from 7 September 2015 12 UTC of ~~the~~ geopotential height ~~with~~of 1 dm interval (blue lines, the 76 dm line is passing over Israel~~; blue lines~~) and wind (red arrows, 10 KT each line~~; red arrows~~). Source: IMS from UKMO British Met Office model.

The fact that forecast models did not succeed in predicting this outstanding dust event motivated Mamouri et al. (2016) to study its origin and development. Their research presented dust load observations in the Cyprus region. Luckily, at the time of the dust storm, an EARLINET (European Aerosol Research lidar Network: https://www.earlinet.org/) Raman lidar stationed in Limassol provided vertical dust profiles and valuable optical dust properties of backscatter, extinction, lidar ratio and linear depolarization ratio. They analyzed the optical thickness (AOT) and Angström exponent derived from the MODIS Aqua satellite. MODIS Aqua AOT measurements were compared to the Limassol lidar observations, AOD measurements from two AERONET sites (Cyprus and Israel) and ground level PM10 concentration from four Cyprus sites. On 7 September, EARLINET lidar observations measured two dust layers (extending up to 1.7 km ASL and between 1.7-3.5 km ASL). The dust particle extinction coefficient measured in Limassol had reached 1000 Mm^{-1} followed by high PM10 concentration of 2000 µm m^{-3}. Extreme values over Limassol, were reported on ~~the~~ 8 September as MODIS Aqua AOT observations exceeded 5 (assuming overestimation up to 1.5) and hourly PM10 concentration of about 8,000 µm m^{-3} (with uncertainties in the order of 50%). Unfortunately, on ~~the~~ 8 September, the lidar was intentionally shut down to avoid potential damage to the instrument. ~~Nevertheless, lidar~~Lidar observations indicated another dense dust outbreak (1-3 km ASL) reaching Limassol on ~~the~~ 10 September, also visible by ~~the~~AOT MODIS Aqua ~~AOT imagery~~. The researchers concluded the scale of the dust storm features was too small for global and regional dust transport models. They presumed that the initiation of the dust plume was due to an intense dust storm (Habbobhaboob) in northeastern Syria and northern Iraq, leading to vigorous downbursts which consequently pushed huge amounts of dust and sand to the atmosphere. The lidar observations indicated a double layer structure of the dust, 1.5 and 4 km above sea level (ASL),, pointing to multiple dust sources.

StavrosSolomos et al., (2016) continued the investigation of the formation and mechanism of the dust storm over Cyprus by a high regional atmospheric model of the integrated community limited area modeling system (RAMS-ICLAMS). The model simulations focused on the generation of the dust storm on 6 and 7 September. Model results were fine-tuned by observations from EARLINET lidar stationed in Limassol, radiosonde data from five sites (Cyprus, Israel, Jordan, and two from Turkey) and satellite imagery from MSG SEVIRI and CALIPSO CALIOP. The model was set to three grid space domains: an external grid of 12X12 km, (over the EM) an inner set at 4X4 km (over northern EM) and 2X2 km grid for cloud resolving (over northeastern Syria). The vertical structure consisted of 50 terrain following levels up to 18 km. The researchers assessedestimated a strong thermal low over Syria was followed by convection activity over the Iraq-Iran-Syria-Turkey borderline combined. Combined with land use changes (aftermath of the war held in Syria)), these conditions manufactured the extreme dust storm. The model succeeded to describe the dust westward flow of a haboob containing the dust previously elevated over Syria asalso observed by MSG SEVIRI and EARLINET lidar. However, there were some inaccuracies in the quantification of dust mass profiles. TheyThe researchers attributed the model discrepancies to the limited ability of the model to properly resolve dust and atmospheric properties (e.g. change of land use and intense downward mixing).

Evaluation whether the dust activation due to human perturbations to land use (such as in the Syria civil war) had an underlying effect on the dust storm formation or even to its increase were studied by Pu and Ginoux, (2016). They) examined the connection between the natural climate variability (the Pacific decadal oscillation) and the dust optical depth (DOD) in Syria. DOD, between the years 2003-2015. DODs were derived by the deep blue algorithm (Hsu et al., 2013) aerosol product from MODIS Terra and MODIS Aqua satellite (10 km resolution picture) was combined with monthly horizontal winds and geopotential heights generated). AODs were estimated by the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis model (horizontal resolution of 80 km and 37 vertical levels). The dataset of DODs during the years 2003-2015 were compared to) and produced by the Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric model (AM3) (Donner et al., 2011). The In addition, the AM3 model produced AODs and calculated the mass distribution and optical properties of aerosols, their chemical production, transport, and dry or wet deposition. Comparison of AODthe model results,

~~AOD~~AODs, AERONET AOD measurements and ~~DOD~~DODs from satellite observations revealed the model underestimated the ~~AOD's~~AODs particularly in the EM. The authors assumed that the soil moisture parameter in the model were not set properly resulting in the AOD dissimilarities.

The impact of the conflict in Syria on the aridity of the region and therefore, a possible direct impact on the generation of the September dust storm was examined by Parolari et al., (2016). The researchers conducted simulations using the Advanced Research Weather Research and Forecasting (WRF-ARW) model from 30 August 2015 to 10 September 2015 over the EM. The model consisted of two nested domains (9 and 3 km grid spacing and 35 vertical levels). Daily and monthly AOD data from MODIS were computed by the deep blue algorithm over land. ~~Anomalies of the September 2015 monthly average AOD were compared to the monthly average of 2000-2015.~~ The monthly average of September 2015 vegetation status in the region was estimated by MODIS normalized difference vegetation index (NDVI). Historical data was divided into two periods: none-drought (2001-2006) and drought (2007-2010). Wind shear stress was calculated to estimate wind erosion. ~~Their~~Main findings reveal that the enhanced dust uplift and transportation of the September 2015 dust storm was due to meteorological conditions rather than the land-use changes ~~because of~~attributed to the civil conflict in Syria. WRF simulations revealed ~~the well-known Shamal winds and cyclone associated with dust storms in the Middle East (Rao et al., 2003) were characterized by~~ northwesterly winds west of the low pressure zone in the Syrian-Iraqi border~~. However, the~~ were associated with dust storms in the Middle East (Rao et al., 2003). The source of elevated dust concentrations over the EM coast on ~~the 7and~~7 and 8 September were attributed to the cyclone front movement. On 6 September low level winds (700 hPa) were opposite to the northwesterly high level winds (300 hPa~~) winds,~~), consequently~~,~~ generating enhanced surface shear stress and transported re-suspended PM westward. Furthermore, based on the past 20 years, the Israeli summer of 2015 was unusually dry and hot and therefore enabled easier updraft of dust soil increasing the probability of dust emissions.

Jasmin (2016) compared the dust ~~storm~~plume aerosol content provided by MSG SEVIRI observations, to the ~~results~~generation of the dust storm produced by the open source Meteoinfo model (Wang, 2014). The Meteoinfo model was based on meteorological variables from ECMWF. The model ~~meteorological conditions suggested~~revealed a formation of two simultaneous dust storms, from northern Syria and ~~from~~ the Egyptian Sinai desert, ~~resulting from~~as a result of updrafts created by low pressure systems.

____The aforementioned studies (summarized in Table 1) focused on the generation of the dust storm in the Syria region based on transport models, satellite imagery and in situ measurements. In our study we focus on the evolution of the dust plume over Israel in the lower atmosphere based on an array of 8 ceilometers~~, 52 in situ PM measurements, two AERONET sites and satellite imagery. We do not investigate the reasons of the models frailer to predict this extraordinary storm, but rather attempt to present details of the evolution of the dust plume passage over Israel. The data presented here can be used as a tool to verify state of the art model simulations and provide a different point of view to the meteorological conditions governing the dust plume advection over the EM.~~

~~In the following section we describe the measuring sites and instruments in this study.~~ and auxiliary instruments described in Sect. 2. The list of instruments includes; ceilometers, PM measurements, AERONET, radiosonde, solar radiation and satellite imagery. Sect. 3 presents the ~~results~~delineation of the dust plume spatial and temporal scheme ~~delineated by the ceilometer plots on~~from 7 ~~September through the~~ 10 September 2015. We discuss and compare the results between the ~~ceilometer plots and the aforementioned auxiliary~~different measurements. ~~In Sect. 4 we conclude our~~ Conclusions and main findings of the dust plume ~~advection~~progress in the lower atmosphere ~~above Israel and the downward transport towards the ground.~~are given in Sect. 4.

2. Instruments

2.1 Ceilometers

Lidars are widely used for aerosol studies (Ansmann et al., 2011; Papayannis et al., 2008) including desert dust characteristics and transport process (Mona et al., 2012). Ceilometers, initially intended for cloud level height detection, are automatic low cost lidars widespread in airports and weather stations worldwide. As single wavelength lidars, ceilometers cannot produce the information aerosol properties such as size distribution, scattering and absorption coefficients. ~~(Ansmann et al., 2011; Papayannis et al., 2008).~~ Nevertheless, with improvement of hardware and firmware over the years, ceilometers have become a valuable tool in the study of the atmospheric boundary layer and the vertical distribution of aerosols layers (Haeffelin and Angelini, 2012; Ansmann et al., 2003). Furthermore, in 2013 ceilometers ~~been~~were assimilated in the EUMETNET (European Meteorological Services network) ~~Profiling Program (E~~Eprofiling program across Europe (http://eumetnet.eu/activities/observations-programme/current-activities/e-profile~~) to develop a homogeneous dataset from automatic lidars and state-of-~~/alc-network/). The main research tool in this study is the~~-art~~ Vaisala ceilometers ~~across Europe (http://eumetnet.eu/activities/observations-programme/current-activities/e-profile/alc-network/).~~ type CL31, commonly deployed worldwide.

~~Vaisala ceilometers type CL31, are commonly deployed worldwide, and the main research tool in this study as well.~~ CL31 is a pulsed elastic micro lidar, employing an Indium Gallium Arsenide (InGaAs) laser diode transmitter of near infrared wavelength ~~of~~ (910 nm ±10 nm at 25˚C~~.~~). In order to compensate the low pulse energy of the laser (hence defined "eye-safe") and to provide sufficient signal to noise ratio, the pulse repetition rate is of 10 kHz ~~every two seconds~~ (Vaisala ceilometer CL31 user's guide: ~~http://www.vaisala.com~~ http://www.vaisala.com). The backscatter signals are collected by an avalanche photodiode (APD) receiver and designed into ~~attenuated backscatter~~range corrected signal profiles within a reporting interval of 2-120 s (determined by the user~~).~~) given in relative unites (signal counts). The ~~attenuated backscatter~~ceilometer profiles are automatically corrected by ~~an internal calibration (resulting in a multiplication factor of 10^{-8} to convert the signal count to attenuated backscatter),~~ a cosmetic shift of the backscatter signal (to better visualize the clouds base), an obstruction correction (when the ceilometers' window is blocked by a local obstacle) and an overlap correction (to the height where the receiver field of view reaches complete overlap with the emitted laser beam).

Vaisala provides a scaling factor transferring signal counts to attenuated backscatter units by a multiplication factor of 10^{-8}. The scaling factor was obtained using a calibration procedure operated on a several instruments and cross-checked by signal integral from water clouds. The uncertainty of calibrated attenuated backscatter profile (with a 100% clean window condition) was of ± 10 %. The uncertainty for the estimated attenuated backscatter was of ± 20 % (Münkel C., private communication). However, Kotthaus et al., (2016) emphasize that this internal calibration applied to convert the signal count output to attenuated backscatter units does not always fully represent the actual lidar constant, therefore, it is not accurate enough for meteorological research. Hence, in this study we defined the ceilometer profiles as range corrected signal profiles in arbitrary units.

Kotthaus et al., (2016) examined the Vaisala CL31 ceilometer by comparing ~~the~~ attenuated backscatter profiles from 5 units with different specification of senor hardware, firmware and operation settings (noise, height and time reporting interval). ~~They have concluded~~Research findings show the instrument characteristics that affect the quality and availability of the attenuated backscatter profiles ~~in the following manner~~are as follows: At high altitudes, a discontinuity in the attenuated backscatter profile is evident at two height points, ~ 4949 and 7000 m. Background signals (instrument related) and cosmetic shift (firmware dependent) tend to be either negative or positive up to 6000m and then switch signs above ~ 6000 m. Below 70 m an overlap correction is applied internally by the ceilometer sensor as well as an obstruction correction (below 50 m). Between 50-80 m hardware related perturbation cause a slight offset in the attenuated backscatter values. The authors advise the user-defined reporting interval should be no shorter than 30s to avoid consecutive profiles partial overlap. ~~However, they emphasize the internal calibration applied to convert the signal count output to “attenuated backscatter” does not always fully represent the actual lidar constant, therefore, it is not accurate enough for meteorological research. Nevertheless, since ceilometers are not sensitive to molecular scattering and solar radiation contributes to the random noise, a background correction can be derived by a 4 hr round of midnight attenuated backscatter profiles. Furthermore, a~~Background noise reduction can be achieved by a procedure based on long averaging period at nighttime during a clear atmosphere. A range corrected attenuated backscatter can be derived by the attenuated backscatter profiles during an existence of a stratocumulus cloud.

~~Furthermore,~~ Weigner et al, (2014) studied different retrieval methods to derive the aerosol backscatter coefficient from the ceilometers' attenuated backscatter profiles based on a comparison to auxiliary collocated instruments such as a ~~sunphotmeter~~Sunphotmeter or a multiwavelength lidar. They focused on calibration methods, the rage detection limitations by the overlap function and the sensitivity of the attenuated backscatter signal to relative humidity. Although, the ceilometer wavelength range (given as 905 ±3 nm) is influenced by water ~~vapour~~vapor absorption, in the case of aerosol layer detection, water ~~vapour~~vapor distribution has a small effect on the signal change, indicating the mixed layer height (MLH) or an elevated mixed layer, as the aerosol backscatter itself remains unchanged~~.~~ (Wiegner and Gasteiger, 2015). Consequently, except for a case of a dry layer in a humid MLH, ~~the~~ water ~~vapour~~vapor is unlikely to lead misinterpretation of the aerosol stratification. Fortunately, most algorithms are based on a significant signal slope to define the aerosol layers, therefore, can be determined from ~~uncelebrated~~uncalibrated ceilometer attenuated backscatter profiles.~~The wavelet covariance transform (WCT) was the method used in this study to evaluated the MLH (Uzan, et al, 2016), whether determined by the creation of thermals or the subsidence of the dust plume.~~

~~In this study, we address the aforementioned limitations as we refer to the ceilometer signal count profiles between 100-1000 m AGL. The~~In this research, ceilometer array is comprised of 8 units in different sites (Fig 3 and Tables 2-3), 6 of which are owned by a governmental office. The ceilometers are CL31 type apart for ceilometer CL51 stationed in the Weizmann Institute which has a higher backscatter profile range (up to 15.4 km, Münkel et al., 2011). Unfortunately, calibration procedures were not held and maintenance (cleaning of the ceilometer window) was done regularly only ~~for~~in the Beit Dagan ceilometer. Apart from the Beit Dagan and Weizmann ceilometers ~~(Table 4),~~ we could not retrieve the technical information of firmware and hardware type~~.~~ (Table 4). However, we have been confirmed (personal communication) that the combination of hardware and firmware had been done following Kotthaus et al (2016). The Beit Dagan ceilometer signal count were found to be weaker (up to 800 signal count compared to 10,000 in the other CL31 ceilometers) due to different hardware definitions. Therefore, in order to present the Beit Dagan ~~attenuated backscatter~~range corrected signal profiles aligned with the profiles of the other ceilometers (given in Fig. 17), the Beit Dagan ~~attenuated backscatter~~range corrected signal values were multiplied by 12.5 (10,000/800). We address the aforementioned limitations of the ceilometers measurements in the first range gates as we refer to the ceilometer signal count from 100 m AGL. Due to the extreme AOD values of the September dust storm, high extinction of the ceilometer signal limited the height of profile analyzed down to 1000 m AGL.

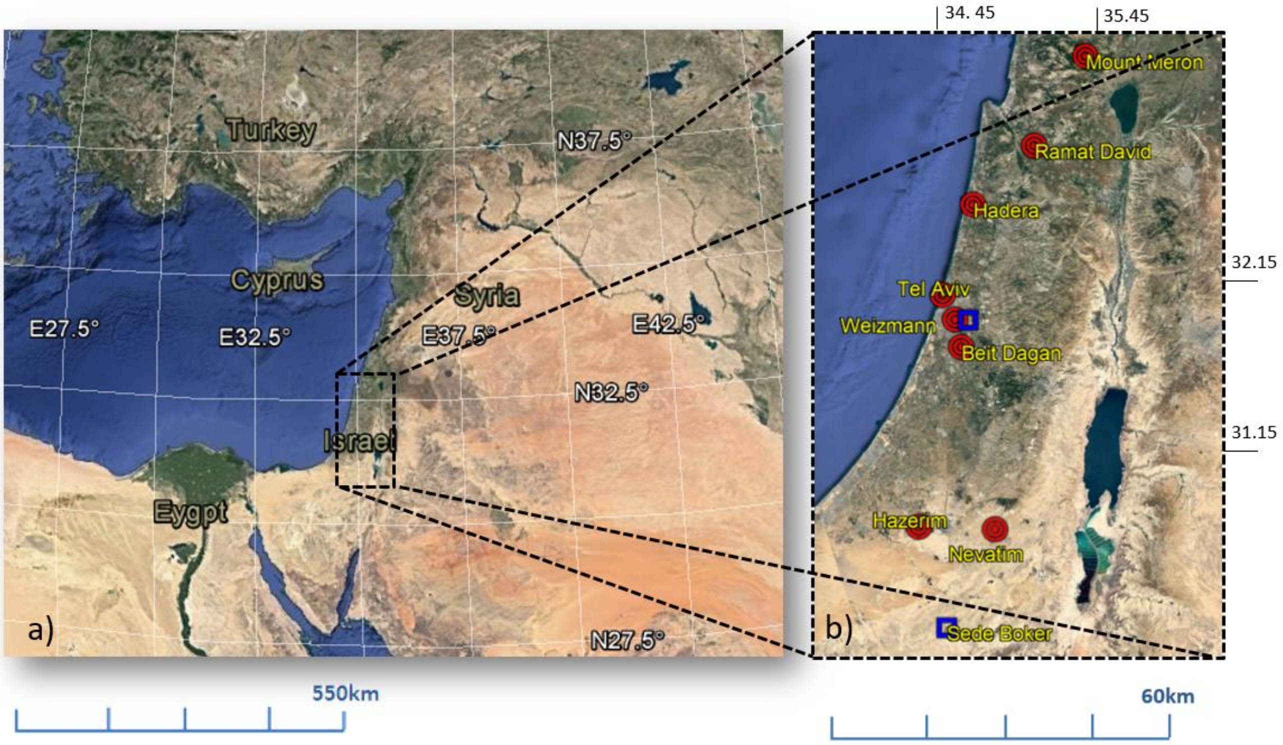


Figure 3. Google Earth map of the large domain (a) and Israel (b) with indications of 8 ceilometer sites (red circle; detail in Table 2) and two AERONET sites (blue square).

2.2 Radiosonde

Radiosonde (RS) type Vaisala RS41-SG is launched by the IMS twice a day at 00 UTC and 12 UTC from the Beit Dagan site adjacent to the Beit Dagan ceilometer. The radiosonde produces profiles of humidity, temperature, pressure, ~~and~~ wind speed and wind direction. The output files were downloaded from the University of Wyoming site (http://weather.uwyo.edu/upperair/sounding.html, station number 40172). With respect to Stull (1988), the MLH was defined by the RS profiles as the height where ~~the following phenomena were identified:~~ an inversion in the temperature~~,~~ was identified along with a significant drop in ~~the~~ relative humidity, strong wind shear and an increase in the virtual temperature (Uzan et al., 2016; Levi et al., 2011).

2.3 Particulate matter monitors (PM10, PM2.5)

PM monitors are low-volume flow rate Thermo Fisher Scientific type FH 62 C14 (beta attenuation method) and type 1405 TEOM (Tapered Element Oscillating Microbalance method). Both instruments report PM concentration every 5 min. The location of PM measurement sites is given in Tables 5. In the beta attenuation method ~~(https://www3.epa.gov/ttnamti1/files/ambient/inorganic/overvw1.pdf)~~(https://www3.epa.gov/ttnamti1/files/ambient/inorganic/overvw1.pdf) low-energy beta rays are focused on deposits on a filter tape and attenuated according to the approximate exponential function of particulate mass (i.e., Beer's Law). These automated samples employ a continuous filter tape. The attenuation is measured through an unexposed portion of the filter tape~~ is measured, the~~. The tape is then exposed to the ambient sample flow where a deposit is accumulated. The beta attenuation is repeated, and the difference in attenuation between the blank filter and the deposit is a measure of the accumulated concentration. The weighing principle used in the TEOM method ~~(https://tools.thermofisher.com/content/sfs/manuals/EPM-TEOM1405-Manual.pdf)~~(https://tools.thermofisher.com/content/sfs/manuals/EPM-TEOM1405-Manual.pdf) is based on a mass change detected by the sensor as a result of the measurement of a change in frequency. The tapered element at the heart of the mass detection system is a hollow tube, clamped on one end and free to oscillate at the other. If additional mass is added, the frequency of the oscillation decreases~~.~~ and a precision electronic counter measures the oscillation frequency with a 10-second sampling period. An electronic control circuit senses oscillation and adds sufficient energy to the system to overcome ~~losses. An~~lossesd while an automatic gain control circuit maintains the oscillation at a constant amplitude. ~~A~~

~~precision electronic counter measures the oscillation frequency with a 10-second sampling period. Both instruments report PM concentration every 5 min. The location of PM measurement sites is given in Tables 5.~~

2.4 AERONET

AErosol RObotic NETwork (AERONET) is multiband photometer with an automatic sun tracking radiometer for direct sun measurements with a spectral range of 340 ~~to~~- 1640 nm wavelengths. The photometer measures the solar extinction in each wavelength to compute aerosol optical depth (Holben et al., 1998). In Israel~~ two~~, AERONET units type CE318-N (https://aeronet.gsfc.nasa.gov) operate in Sede Boker and the Weizmann Institute (Fig. 3). Unfortunately, the unit in Weizmann did not operate ~~during~~between 6-8 September 2015 due to power failure. ~~In~~For this study~~ we used~~, data acquisition was comprised of AOD (500 nm wavelength) and Ångstrom exponent (440-870 nm wavelengths) based on AERONET Level 2.0 ~~data~~ (cloud screened and quality assured for instrument calibration~~) for AOD at 500 nm and the Ångstrom Exponent defined by 440-870 nm.~~).

2.5 Global, direct and diffuse solar radiation measurements

Global solar radiation is measured ~~in~~ by ~~IMS in 22 sites (Table. 6) by instrument type~~ Kipp & Zonen pyranometer ~~CMP-11. Integrated solar radiation~~ type CMP-11 in 22 sites (Fig. 20) operated by the IMS. The pyranometer produces 10 min measurements of the integrated radiation flux (W m^{-2}) ~~from~~between 300~~ to~~ -3000 nm ~~is produced every 10 min.~~wavelengths. Diffuse and direct radiation are also measured in Beit Dagan (coastal region, 31 m ASL) and Beer Sheva (southern region, 71 m ASL). For diffuse radiation measurements, a ring is ~~installed~~mounted over ~~the~~a pyranometer to ~~shade~~avoid direct solar radiation. Direct radiation is measured by a sun tracker pyrheliometer.

2.6 Satellite imagery

2.6.1 SEVIRI (MSG satellite)

Meteosat Second Generation (MSG) is a new series of European geostationary satellites operated by EUMETSAT (European Organization for the Exploitation of Meteorological Satellites). On board the MSG is a 12-channel Spinning Enhanced Visible and Infrared Imager (SEVIRI) (Roebeling et al., 2006). The combination of red, blue and green (RGB) channels (12-10.8 µm, green:10.8-8.7 µm, blue:10.8 µm, respectively) produce imagery of dust in pink or ~~magneta~~magenta, dry land in pale blue at daytime and pale green at nighttime~~, thick~~. Thick high-level clouds in red-brown tones and thin high-level clouds appear nearly black ~~(http://oiswww.eumetsat.int/).~~(http://oiswww.eumetsat.int/). Access to EUMETSAT imagery is ~~given in https://www.eumetsat.int/website/home/Images/RealTimeImages/index.html.~~provided online by https://www.eumetsat.int/website/home/Images/RealTimeImages/index.html. Several studies compared AOD from MGS SEVIRI and AERONET measurements (Romano et al., 2013; Bennouna et al., 2009; Jolivet et al., 2008) ~~compared AOD from MGS SEVIRI and AERONET measurements clarified~~showed the uncertainty of MSG SEVIRI AOD decreases as AOD rises. For continental aerosol type, errors do not exceed 10 % in viewing zenith angles between 20° and 50~~°, probable for the study area considered here. Overall, the~~. The MSG SEVIRI AOD uncertainty it is expected to be under 15% (Mei et al, 2012) and even higher as the atmospheric AOD increases above 1.5 (EUMETSAT Scientific Validation Report SEVIRI Aerosol Optical Depth (23 Oct 2017). North Africa Sand storm survey (NASCube: http://nascube.univ-lille1.fr) obtains AOD by temperature anomalies ~~of~~based on SEVIRI RGB by evaluating the difference in the emissivity of dust and desert surfaces during daytime.

2.6.2 MODIS (Terra and Aqua satellites)

The MODerate resolution Imaging Spectrometer (MODIS) instrument ~~flies~~is stationed aboard the Earth Observation System's (EOS) Terra and Aqua polar-orbiting satellites~~, with~~. Terra satellite is on a descending orbit (southward) over the equator ~~about~~at ~ 10:30 local sun time~~, and~~. The Aqua satellite is on an ascending orbit (northward) over the equator ~~about~~at ~ 13:30 local sun time. MODIS performs measurements by 36 channels between 412 ~~to~~ -14200 nm whereas the aerosol retrieval makes use of seven channels (646, 855, 466, 553, 1243, 1632 and 2119 nm central wavelength~~), and~~) together with a number of other wavelength bands ~~associated with~~ for screening procedures. Remer et al., ~~As land signals (AERONET) and the atmospheric signals are comparable at ~ 550 nm,~~(2006) revealed errors of 0.01 in ~~assumed~~the MODIS surface reflectance will lead to errors on the order of 0.1 in AOD retrieval ~~(~~. However, under conditions of high AOD (<1.5) the uncertainty is expected to rise.~~Remer et al., 2006).~~

2.6.3 CALIOP (CALIPSO satellite)

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is a two-wavelength polarization lidar (1064 and 532nm) aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) that performs global profiling of aerosols and clouds in the troposphere and lower stratosphere. CALIOP ~~is the primary instrument on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite. CALIOP is required to accurately measure~~measures signal returns in a large range, from ~~the~~ aerosol-free region ~~between 30 and 35 km as well as the strongest~~up to strong cloud returns. ~~Samples acquired~~The CALIOP profiles are given below 40 km for the 532~~-~~ nm channel and below 30 km for the 1064~~-~~ nm channel~~ are downlinked as profile data.~~. Data ~~used here~~acquisition in this research was based on level 2 version 4-10 CALIPSO product~~,~~ of 532 nm wavelength with a spatial resolution of 5 km (20N-50N, 20E-50E) and vertical resolution of 60 m (limited up to 6 km).

3. Results and discussion

The following description of the dust event will proceed chronologically from 7 to 10 September and include main findings ~~of~~from the different measuring instruments (Sect. 2). The order of the instruments described follow the most interesting features revealed, not necessarily in the same order for each day. We provide 2D ceilometer plots (height vs. time) presenting the extreme dust plume decent only from ~ 1km ASL due to the ceilometer limitation to detect signals from higher levels (explained in Sect. 2.1). Unlike the high resolution ceilometers, CALIPSO overpass above Israel was available only on 10 September 2015 revealing dust distribution in various levels up to 5 km ASL.

3.1 7 September 2015

On 7 September, images from MODIS Aqua (Fig. 4a) and MODIS Terra (Fig. 4e) taken between 07:20-12:10 UTC show that the dust plume progressed from northeast in a near-circular motion over the Mediterranean Sea. The penetration of the dust plume to Israel was indicated by AERONET Sede Boker site at ~ 05 UTC by an increase in AOD along a decrease in the Angström exponent (Fig. ~~5) from AERONET Sede Boker site.~~5). The ~~relationship~~connection between ~~the~~decreasing Angström exponent ~~decrease~~values and the ~~mineral~~ dust plume was pointed out by Mamouri et al., (2016~~). They studied the dust layer particle linear depolarization by an EARLINET lidar stationed in Limassol Cyprus and concluded that the~~) which presented values of linear depolarization ratio ~~of~~between 0.25-0.32 on 7~~,~~ and 10 September, ~~indicated~~indicting the dominance of ~~the~~ mineral dust. In addition, an increase in the PM concentration started at ~ 05 UTC (not shown) reaching the highest hourly values of 107 µg m^{-3} PM2.5 (Table 5) and 491 µg m^{-3} PM10 (Table 6) only in the Jerusalem elevated sites (~ 800 m ASL) and only at 22 UTC. This 17-hour gap is shown by the ceilometers' plots (Fig. 6-12) ~~of~~as a downward motion of the dust plume from ~ 04 UTC in all measuring sites except for the elevated Mount Meron site (1150 m ASL, Fig. 13). Following Gasch et al (2017) cold pool outflows concept, the exception of Mount Meron site is supported by the MSG-SEVIRI picture (Fig. 14) showing that the first dust plume was fragmented (Fig.14, red arrow) and the second dust plume (Fig.14, black arrow) had not passed over Israel before 12 UTC. The deep blue scale evident in all Mount Meron ceilometer plots (Fig. 13) indicate total attenuation distinctively from 7 September ~ 14 UTC to 8 September ~ 16 UTC. However, due to the complexity of the dust plume progress (further shown) and the weak signal counts shown up to 3.5 km ASL (before 7 September ~ 14 UTC and after 8 September ~ 16 UTC), the assumption of a total attenuation throughout the period analysed is uncertain. Unfortunately, we did not have auxiliary measurements from the Mount Meron region to justify our assumptions.

~~The full picture of what happened on the 7 September can be further obtained from~~While the MSG-SEVIRI picture at 12 UTC ~~that~~ shows AOD values to be ~~still~~ under 1 in most parts of Israel (Fig. ~~15).~~15), the PM concentrations on ground level were found to be bearable (up to 105 µg m^{-3} PM2.5 and 305 µg m^{-3} PM10, mainly in the Jerusalem elevated sites). At ~~the same time~~12 UTC, Beit Dagan radiosonde profiles show ~~the~~ a characteristic MLH ~~was still high (~~of 700 m ASL~~, –~~ (Fig. 16). ~~And,~~Moreover, at 23 UTC the formation of clouds was indicated by ceilometers' profiles ~~at 23 UTC~~ (Fig. 17 a) ~~show indications of typical cloud presence from~~at 400 m ASL in the shoreline ~~site~~ (Tel Aviv, 5 m ASL) and up to ~700 m ASL in the elevated southern site (Nevatim, 400 m ASL). Clouds are identified by the peak shape of the ceilometer profiles (Uzan et al, 2016) and the high ~~attenuated backscatter~~range corrected signal of 10 $^{-1}$ m^{-1} sr^{-1} which in this case ~~is~~was 4 orders of magnitude higher than the ~~attenuated backscatter~~range corrected signal of the dust plume (shown in Fig 17 b-c). ~~In spite of the still high MLH and the cloud presence, the~~Hourly solar radiation measurements ~~clearly indicates the significance~~ (Fig. 18, see 7 September daily plot) from Beit Dagan (central site) and Beer Sheva (southern site) show a significant effect of the dust plume ~~effect through the~~by a decrease ~~of the daily~~in direct radiation along with an increase of ~~the~~ diffuse radiation ~~(Fig. 18, see 7 September daily variation) measured both in central Israel (Beit Dagan) and southern Israel (Beer Sheva).~~.

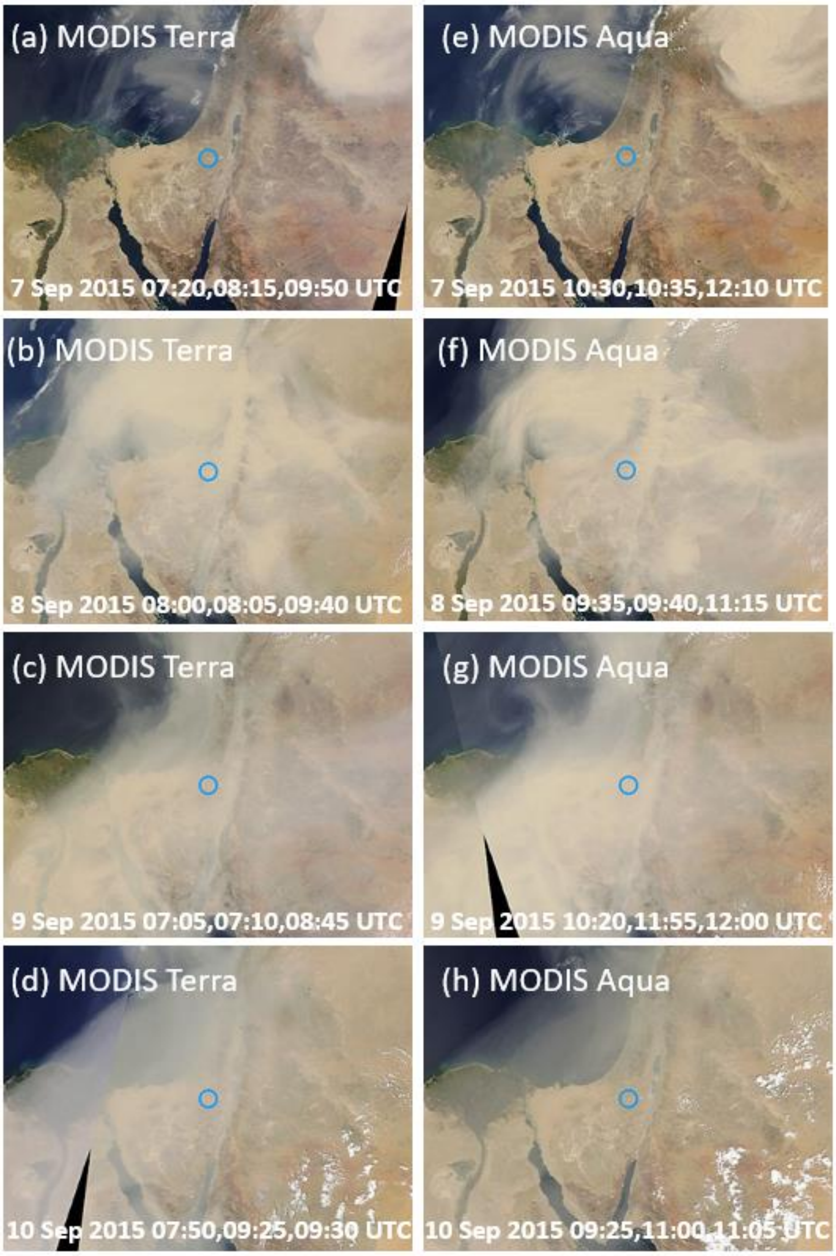


Figure 4. Pictures from MODIS terra (a-d) and MODIS Aqua (e-h). The date and time of overpass are indicated on each figure. ~~Blue~~The blue circle ~~indicating~~indicates the location of the AERONET Sede Boker site. Source: https://aeronet.gsfc.nasa.gov.

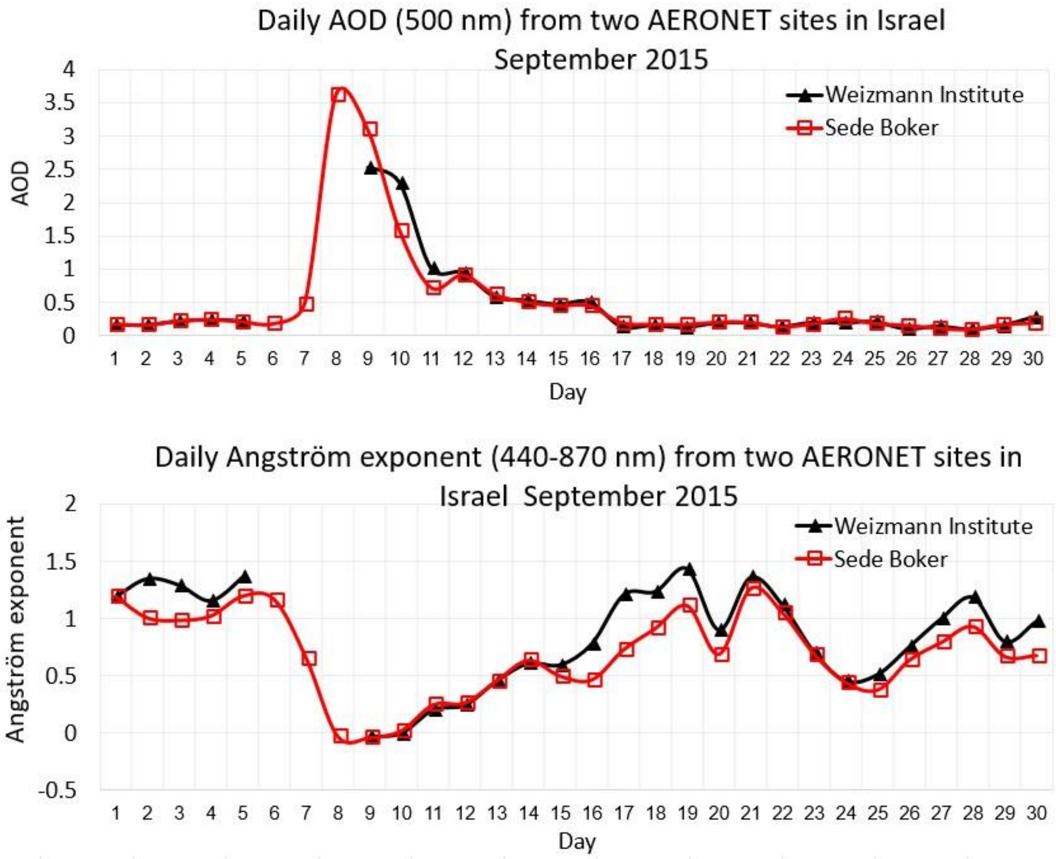


Figure 5. September 2015 daily average of AOD (top panel) and Angström exponent (bottom panel) from two AERONET sites in Israel (Sede Boker and Weizmann, see Fig.3). The Weizmann AERONET did not operate on 6-8 September due to power failure.

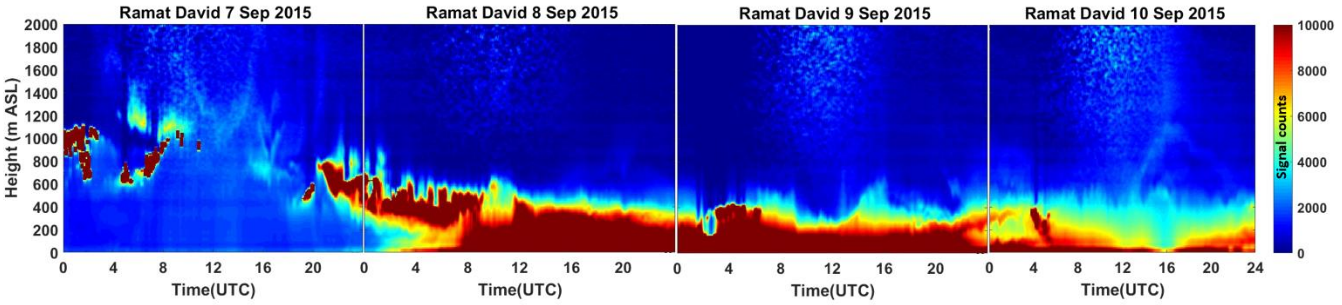


Figure 6. Ramat David ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height up to 2000 m ASL, X-axis is the time in UTC, signal count scale range between 0-10,000.

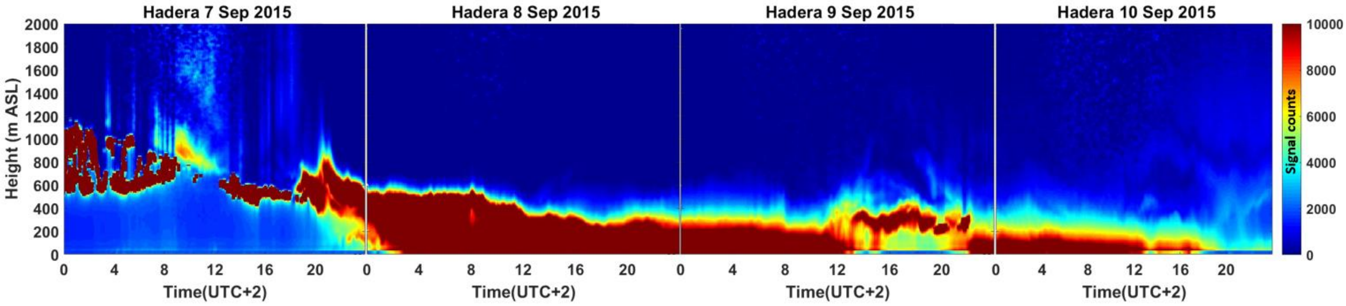


Figure 7. Hadera ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is the time in LST (UTC+2), signal count scale range between 0-10,000.

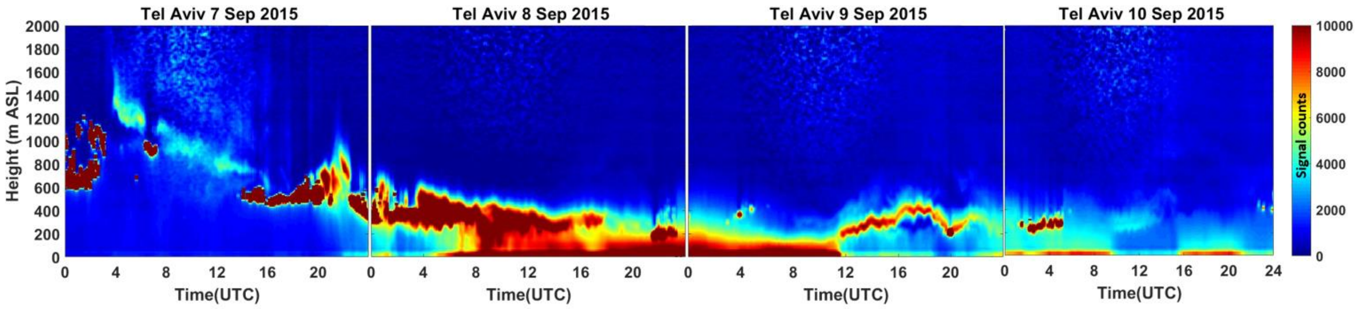


Figure 8. Tel Aviv ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is the time in UTC, signal count scale range between 0-10,000.

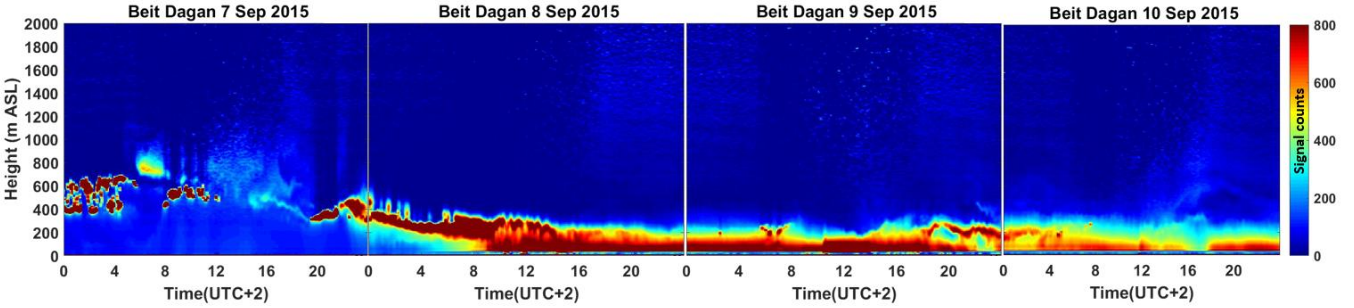


Figure 9. Beit Dagan ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is in LST (UTC+2), signal count scale range between 0-800.

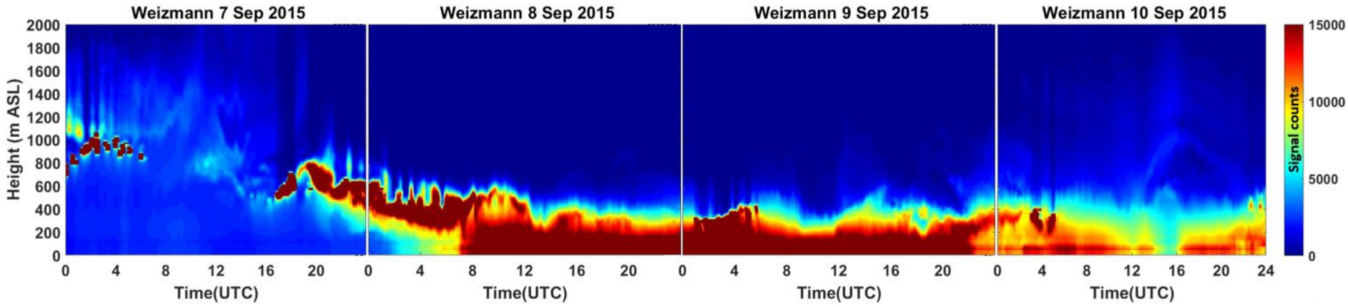


Figure 10. Weizmann ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is in UTC, signal count scale range between 0-15,000.

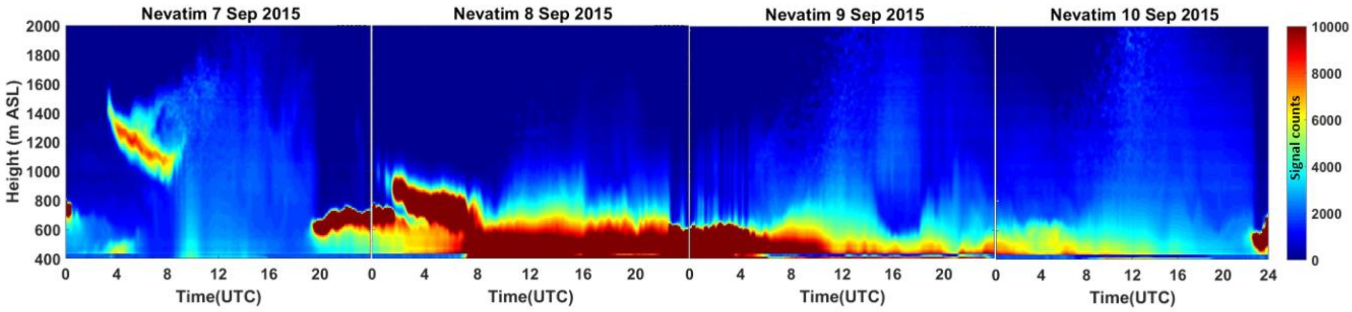


Figure 11. Nevatim ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is the time in UTC, signal count scale range between 0-10,000.

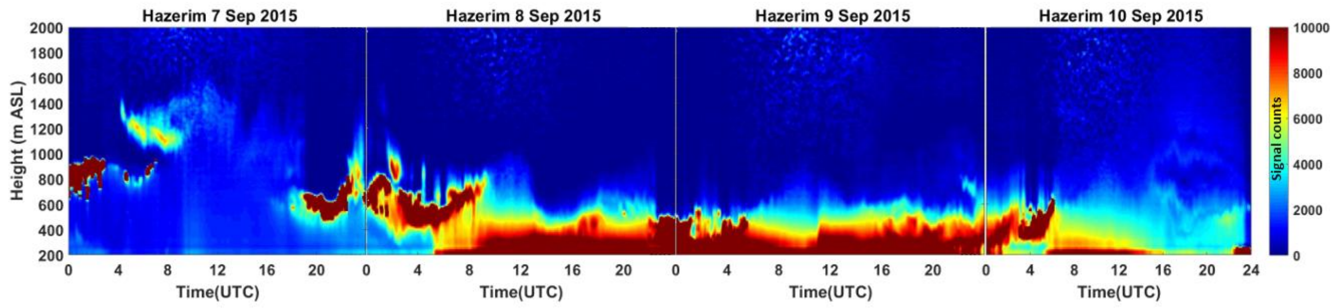


Figure 12. Hazerim ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to 2000 m ASL, X-axis is the time in UTC, signal count scale range between 0-10,000.

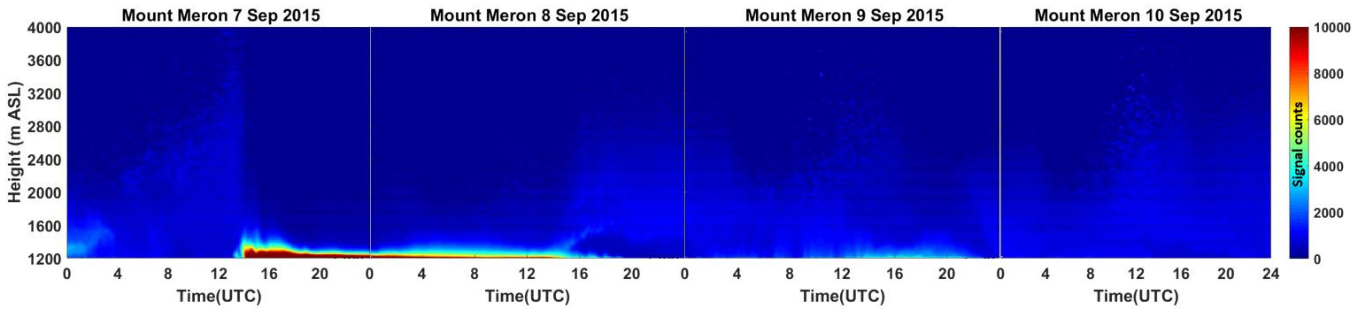


Figure 13. Mount Meron ceilometer signal counts plots for 7-~~9~~10 September 2015. Y-axis is the height from site deployment to ~~2000~~4000 m ASL, X-axis is the time in UTC, signal count scale range between 0-10,000.

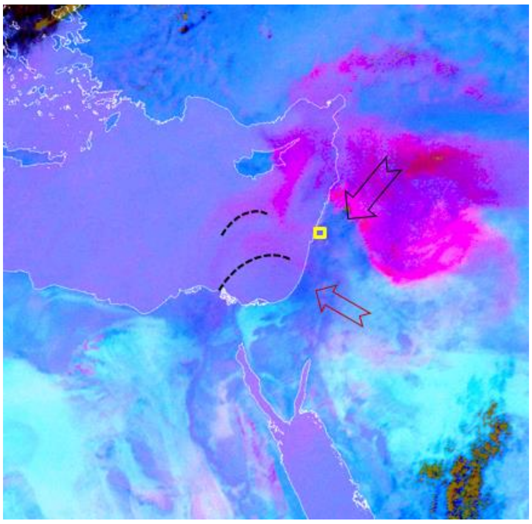


Figure 14. Picture from MSG-SEVIRI satellite of the dust RGB component (dust appears in pink colors) ~~at 12 UTC~~on 7 September 2015 12 UTC with indications of Mount Meron ceilometer site (yellow square, Lon 33.0˚, Lat 35.4˚) and the dust plumes progression from east to west (red arrow and dashed lines) and from the northeast to southwest (black arrow).

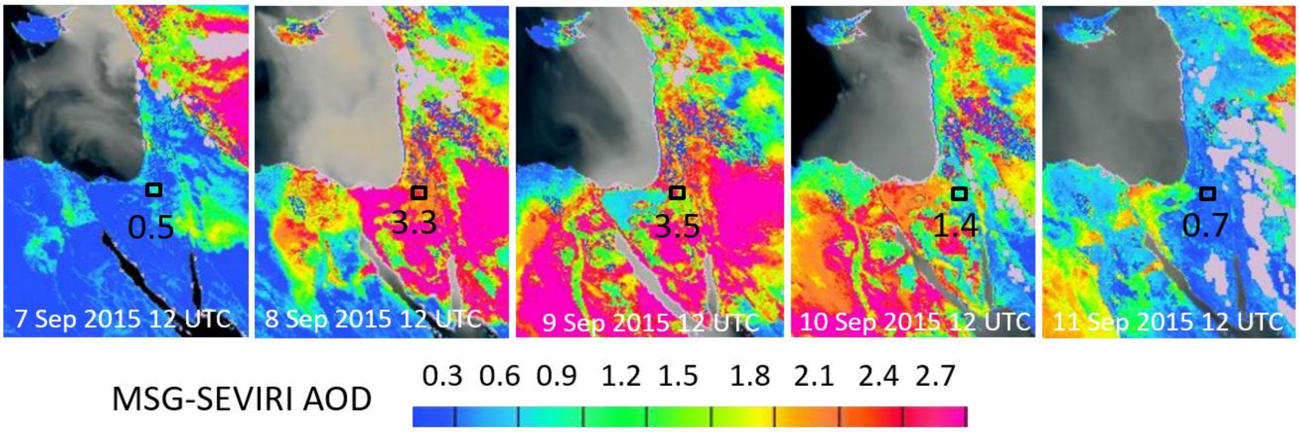


Figure 15. Aerosol Optical Depth (AOD) at 12 UTC 7-11 September 2015 analyzed by ~~NAScube~~NASCube (Université de Lille) based on imagery from the MSG-SEVIRI satellite (by a combination of the SEVIRI channels IR8.7, IR10.8 and IR12.0 ~~channels~~). The map includes indication of the Sede Boker AERONET site (black square) and its AOD value at 12 UTC.

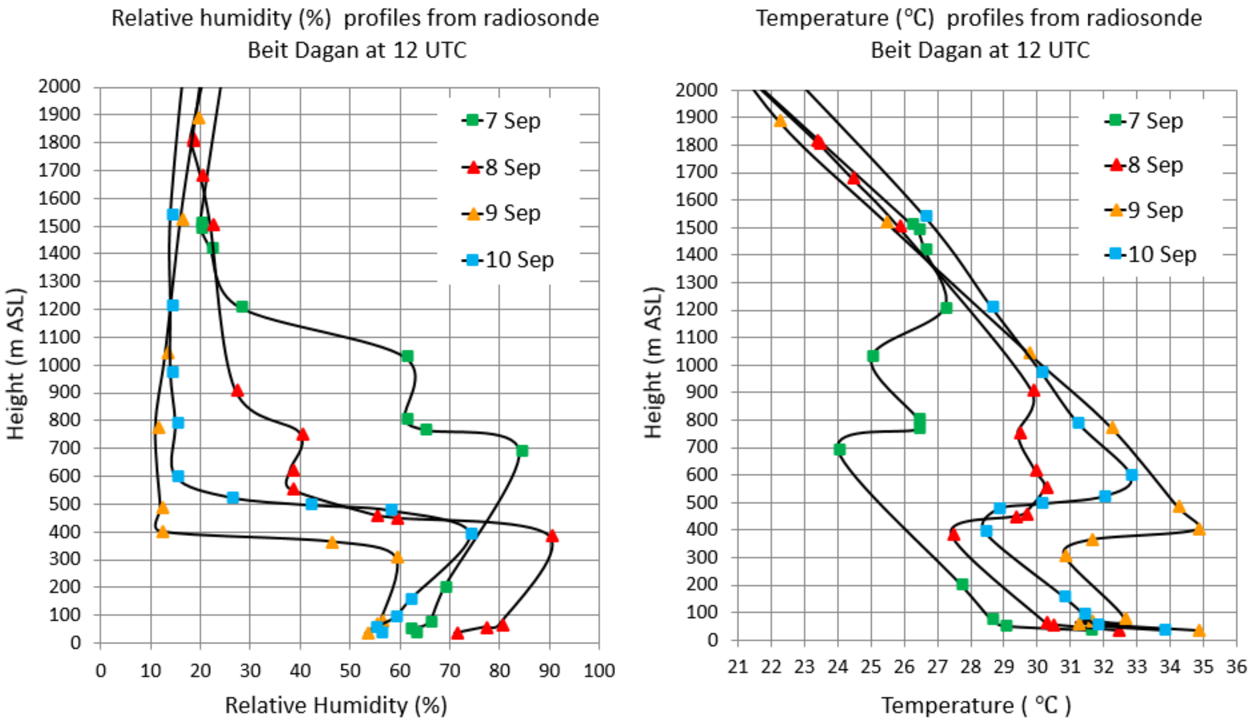
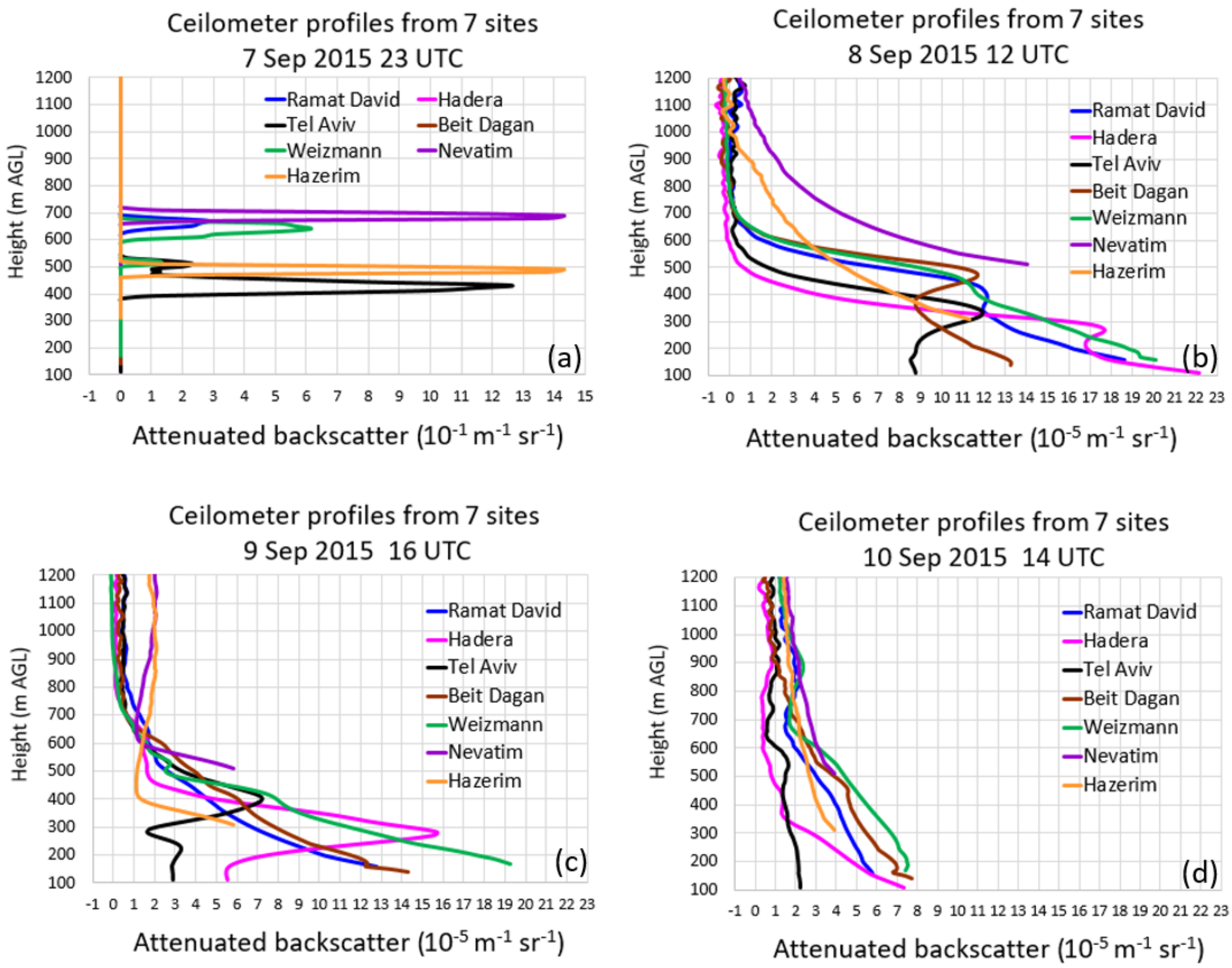


Figure 16. Radiosonde Beit Dagan profiles at 12 UTC between 7-10 September 2015 of relative humidity (left panel) and temperature (right panel).


Ceilometer profiles from 7 sites
7 Sep 2015 23 UTC
Ramat David
Hadera
Tel Aviv
Beit Dagan
Weizmann
Nevatim
Hazerim
Height (m AGL)
(a)
Attenuated backscatter (10-1 m-1 sr-1)
Ceilometer profiles from 7 sites
8 Sep 2015 12 UTC
Ramat David
Hadera
Tel Aviv
Beit Dagan
Weizmann
Nevatim
Hazerim
Height (m AGL)
(b)
Attenuated backscatter (10-5 m-1 sr-1)
Ceilometer profiles from 7 sites
9 Sep 2015 16 UTC
Ramat David
Hadera
Tel Aviv
Beit Dagan
Weizmann
Nevatim
Hazerim
Height (m AGL)
(c)
Attenuated backscatter (10-5 m-1 sr-1)
Ceilometer profiles from 7 sites
10 Sep 2015 14 UTC
Ramat David
Hadera
Tel Aviv
Beit Dagan
Weizmann
Nevatim
Hazerim
Height (m AGL)
(d)
Attenuated backscatter (10-5 m-1 sr-1)

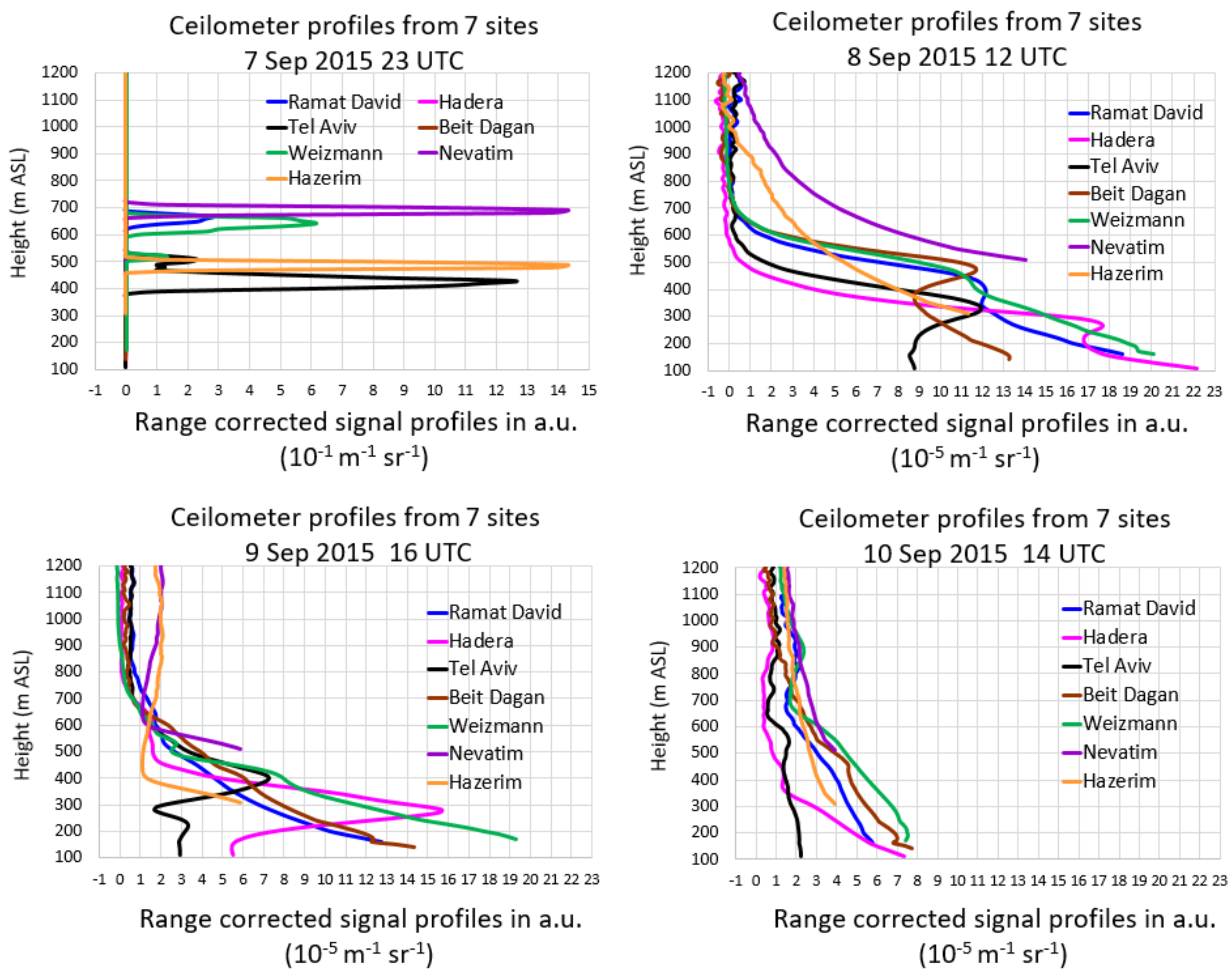


Figure 17. Ceilometer ~~attenuated backscatter~~range corrected signal profiles (in arbitrary units) from 7 sites (Ramat David, Hadera, Tel Aviv, Beit Dagan, Weizmann, Nevatim and Hazerim, see locations in Fig. 3) ~~at 23 UTC~~on 7 Sep 2015 23 UTC (a), 8 September 2015 ~~at~~ 12 UTC (b), 9 September 2015 ~~at~~ 16 UTC (c) and 10 September 2015 ~~at~~ 14 UTC (d). Notice each profile begins ~~relative~~relativily to the height of its' measuring site (ASL) including a deletion of data from the first 100 m AGL due to inaccuracies in the first range gates of the ~~CL31~~ ceilometers (for details see Sect. 2.1). Fig (a) shows cloud detection therefore it ~~has~~is given in a different scale (10^{-1} m^{-1} sr^{-1}) and a different x-axis range.

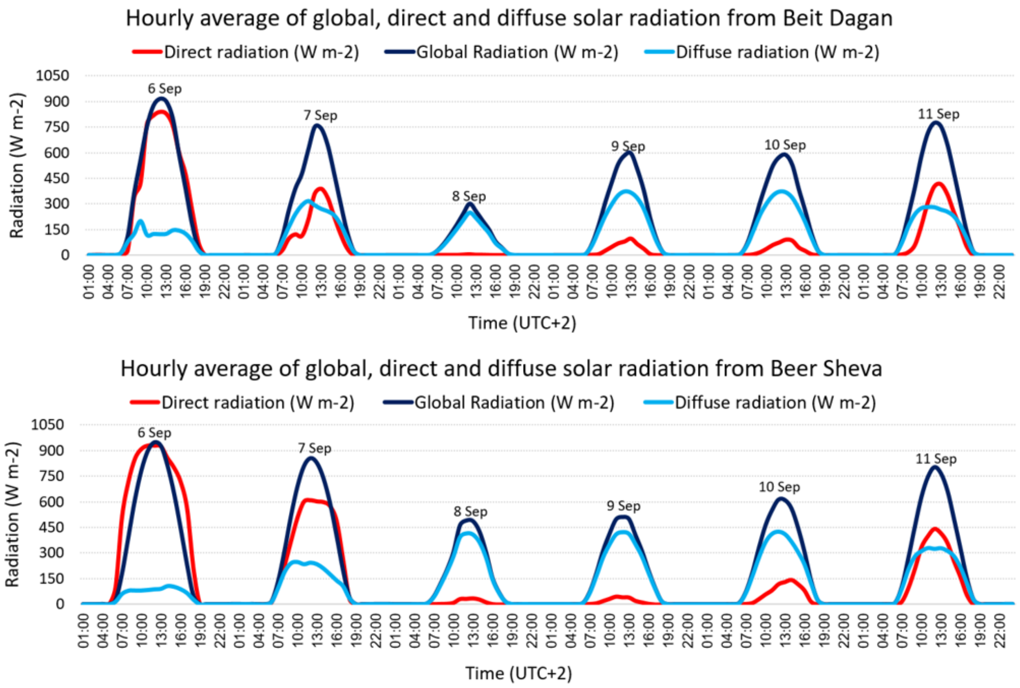


Figure 18. Hourly average of global, direct and diffuse solar radiation between 6-11 September 2015 from Beit Dagan and Beer Sheva.

3.2 8 September 2015

The main phase (the peak) of the dust storm occurred on 8 September. Images from MODIS Aqua (Fig. 4b) and MODIS Terra (Fig. 4f) taken between 08:00-11:15 UTC show the dust storm ~~prevalence~~prevailed over Israel. Ceilometers' plots detect the descending motion of the dust plume reached ground level at ~ 08 UTC (Fig. 6-12). Simultaneously, Sede Boker AERONET AOD measurements increased up to ~4 along with a negative Angström exponent (not shown).

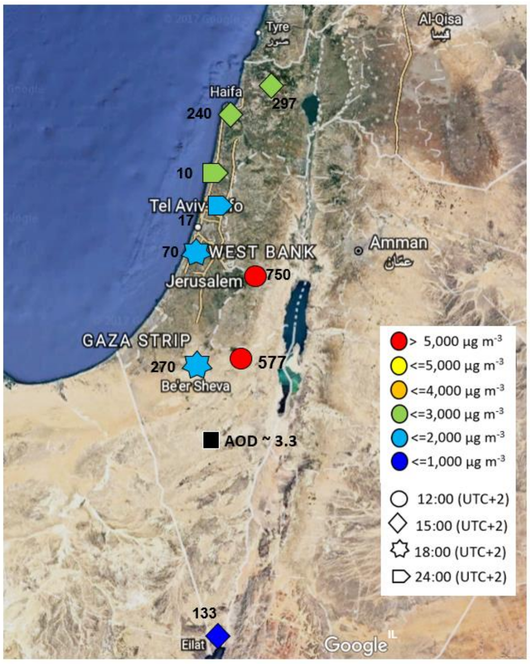
An hour later, at ~ 09 UTC, extreme maximum PM hourly values were measured in the elevated sites of Jerusalem Safra (10,280 µg m^{-3} PM10) and Jerusalem Bar Ilan (3,063 µg m^{-3} PM2.5). Whereby, in the coast and the lower northern regions, maximum PM values were measured only 14 hours later at ~23 UTC and were much lower (up to 3,459 µg m^{-3} PM10 and 470 µg m^{-3} PM2.5, see Tables 5-6). Fig. 19 illustrates the spatio-temporal variation of the PM10 extreme values, beginning at ~ 12 UTC in the elevated Jerusalem sites and ending at midnight in the shoreline.

~~Ceilometer~~At ~08 UTC ceilometer plots from Tel Aviv, Beit Dagan, Weizmann and Hadera (with ~~plot~~a higher scale range of 0-15,000, not shown here~~), Beit Dagan and Weizmann,~~) reveal ~~a two~~ an ununiformed dust layer~~ shape~~, (beneath and above ~ 300 m ASL) ~~starting from ~08 UTC. This two-layer shape later on~~that eventually combined into one dense layer. This ~~pattern~~process may explain the spatial variation and time delay between the extreme PM measurements in the elevated vs. lower sites.

~~Referring to satellite imagery on 8 September,~~

MSG-SEVIRI at 12 UTC ~~(Fig. 15) underestimated~~estimated AOD to be 2.7 while Sede Boker AERONET measured a higher value of 3.3~~.~~ (Fig. 15). Furthermore, MODIS images (Fig. 4a, 4b) show a dominant dust plume over Israel, ~~while~~whereas solar global radiation measurements (Fig.20a) ~~show~~present significant spatial variations ~~in the reduction of the global radiation measured in the different regions. Minimum~~as minimum values (down to 200 W m^{-2}) were measured mainly in northern Israel. ~~This may infer the complex behavior of the dust dispersion in contrary to satellite imagery of a prevailing dust storm over Israel.~~ Additionally, in spite the extreme PM10 values of 9,031 µg m^{-3} measured in the elevated southern site (Negev Mizrahi 577 m ASL, Table 6), the maximum global radiation in southern Israel was still relatively high (~500 W m^{-2}). Generally, the radiative transfer analysis during heavy dust loads is complicated and relies on several parameters such as size, structure and composition of the aerosols (Bauer et al, 2011). Dense dust layers such as in this extreme dust storm definitely had an impact on the radiation budget hence changing weather patterns and air mass transport. The spatial variation of ground level measurements compared to the quit uniform picture revealed by the satellites may infer the complexity of the dust plume evolution.

Overall, 8 September shows the highest PM concentrations and the lowest solar radiation levels for this dust storm event. The solar radiation was composed mainly of diffuse radiation (Fig.18) emphasizing the immense atmospheric dust loads preventing direct insolation. Surprisingly, the low solar radiation was still ~~able~~capable to warm the ground and generate a late and weak sea breeze front (not shown). We assume the insufficient ground heating generated weak thermals that ~~were too weak to create and~~could not inflate a MLH. Therefore, we assume the low MLH (300 m ASL) revealed by ~~the~~radiosonde Beit Dagan profiles from 8 September (Fig.16) ~~which~~ may indicate the dust plume base height. As a result, the ceilometers' plots were fully attenuated above ~300 m ASL.



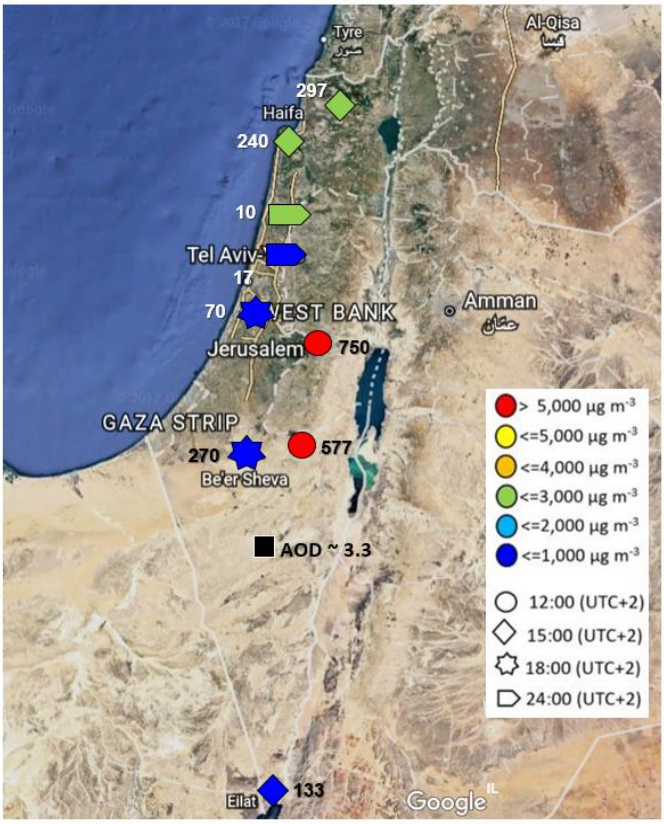
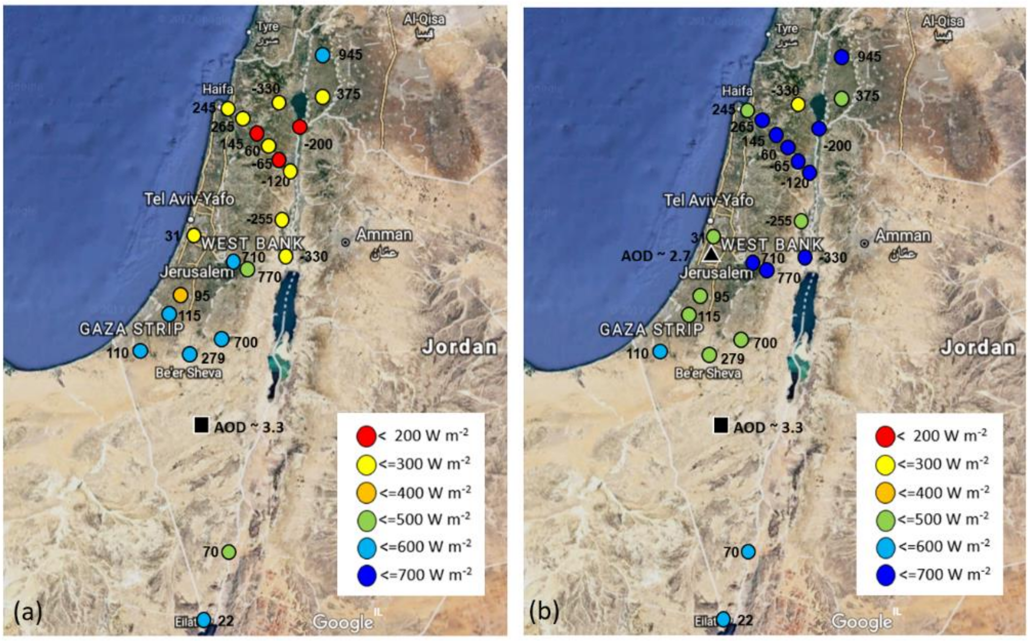


Figure 19. A map of PM10 maximum hourly ~~concentration~~concentrations from 9 sites measured ~~at 10 UTC~~ on 8 September 2015~~.~~ 10 UTC (midday). The map includes indications of the time of measurement (symbol shape), concentration range (symbol color), height of measurement site (numbers ~~in black~~on map) and ~~AERONET~~ AOD from AERONET Sede Boker site.



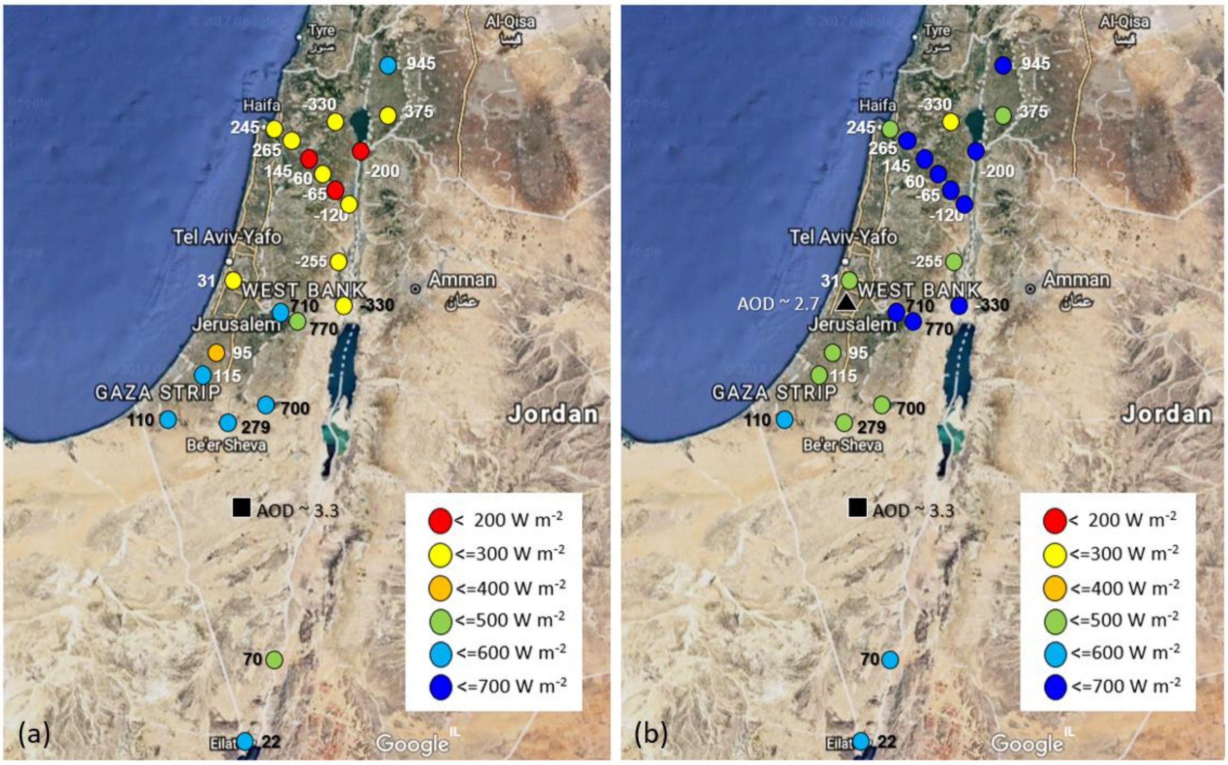


Figure 20. A map of maximum global solar radiation from 22 sites measured at 10 UTC (midday) on 8 September 2015 (a) and on 9 September 2015 (b). The map includes indications of radiation range (see legend), height of measurement site (numbers in blackon the map) and AERONET AOD from AERONET Sede Boker site (black square) and Weizmann site (black triangle). On 8 September the AERONET in Weizmann AERONETsite did not operate due to power failure.

3.3 9 September 2015

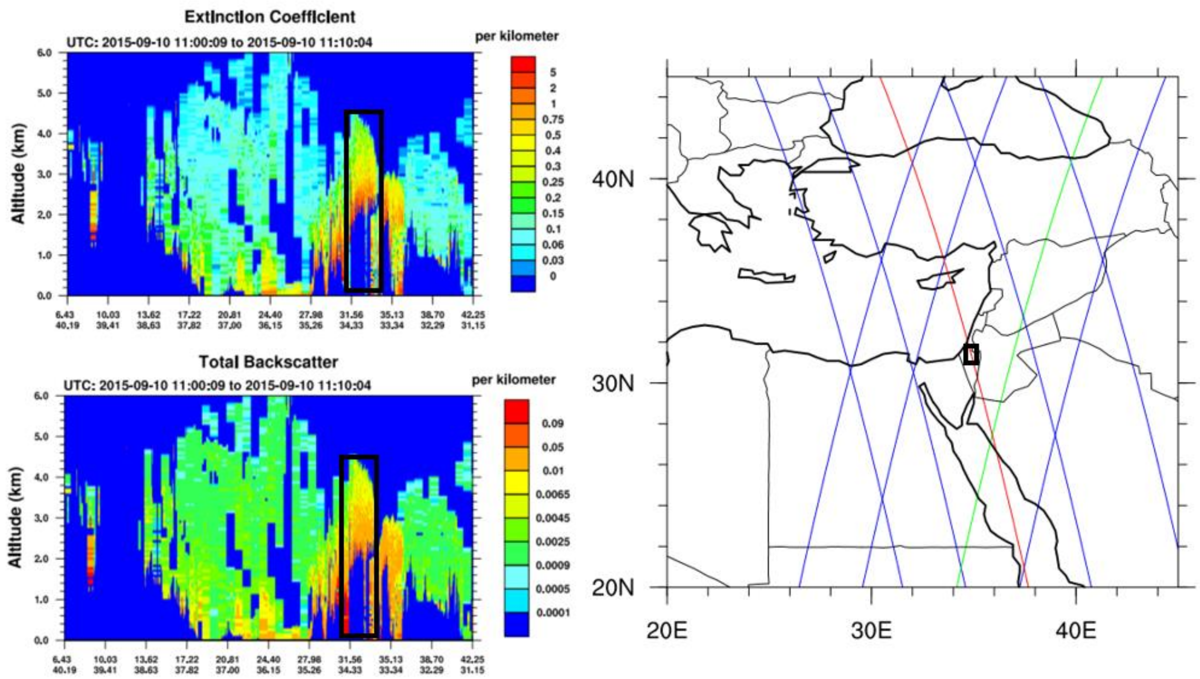
On 9 September, MODIS images (Fig.4c and 4g) taken between 07:05-12:00 UTC show the dust plume progression southward to Egypt (Fig. 4), indicated by Sede Boker AERONET AOD >3 ~~and~~along a negative Angström exponent (Fig. 5). ~~Again, an underestimation of~~ At 12 UTC AOD from MSG-SEVIRI ~~at 12 UTC shows lower AOD~~is~ 2.7 ~~compared to~~whereas Sede Boker AERONET AOD reached up to ~ 3.5 (Fig.15). In contrary to the high AOD measurements, and the descend of the MLH down to ~ 350 m ASL (Fig.16), PM values did not ~~crease~~increase but rather decrease below 900 µg m^{-3} PM2.5 (Table 5) and 4050 µg m^{-3} PM10 (Table 6). The drop in PM concentration gave rise to an increase of solar radiation ~~of~~ up to 400 W m^{-2} (Fig. 20 b). An increase in solar radiation enables significant ground heating to ~~temperature~~ values measured prior to the initiation of the dust storm (not shown). Thus, allowing generation of thermals and the creation of a late the sea breeze cycle ~~which~~ (Uzan et al., 2016). The entrance of the sea breeze front between 11- 12 UTC eventually produced ~~an arc shape~~a narrow dust layer ascent visible in mainly in the coastline -Tel Aviv and Hadera ~~coastal~~ ceilometers ~~beginning at ~ 12 UTC~~ (Fig.7-8). Interestingly, on 9 September, compared to the peak of the dust storm on the day before, we do not see a significant difference in solar radiation in southern Israel, which continued to be relatively high ~500 W m^{-2} (Fig. 20b).

3.4 10 September 2015

On 10 September, MODIS pictures from 7:50 -11:05 UTC (Fig. 4d and 4h) show the dust plume over Israel transported southeast from Syria-Iraq to Sinai-Egypt. The CALIPSO single overpass Israel at 11:00-11:10 UTC revealed a dust layer ~~between 2-4~~up to 5 km ASL (Fig.21). This corresponds with the EARLINET lidar measurements in Limassol, Cyprus (Mamouri et al., 2016) detecting a dust plume between 1-3 km ASL. We assume the CALIOP lidar did not produce data beneath 2 km ASL due to total attenuation. Fortunately, the ceilometers complement the dust profile (beneath ~~1~~~ 1 km ASL) showing a reduction both in signal counts (Fig. 6-12) and in ~~attenuated backscatter~~range corrected signal profiles (Fig.17d) pointing out a reduction in atmospheric dust loads. AOD from MSG-SEVIRI and Sede Boker AEONET show a decrease down to ~~(~~~1.5~~)~~ and a low Angström exponent of ~0.5 indicating prevalence of mineral dust.

~~Furthermore, a~~A profound reduction in PM values, down to a third of the values from the day before (Table 6), was ~~measured~~evident mainly in southern Israel. Therefore, an increase in direct radiation ~~(therefore an increase in global radiation as well)~~ was measured in southern site ~~as well~~ (Fig.18).

The reduction of dust loads may also be denoted by the orange background color of the photograph taken on ~~the~~ 8 September (Fig.1b) compared to the grey background visible on 10 September (Fig.1c). As the dust storm dissipated, cloud formation (indicated by brown spots and evaluated by ceilometer profiles - not shown) was visible from ~~at~~ ~4 UTC by ceilometers ~~plots from~~ Ramat David (Fig.6), Tel Aviv (Fig.8), Weizmann (Fig.10) and Hazerim (Fig.11~~) (indicated by brown spots and evaluated by ceilometer profiles -not shown), otherwise~~). the clouds formation was not evident by MODIS imagery (Fig 4d, 4h).



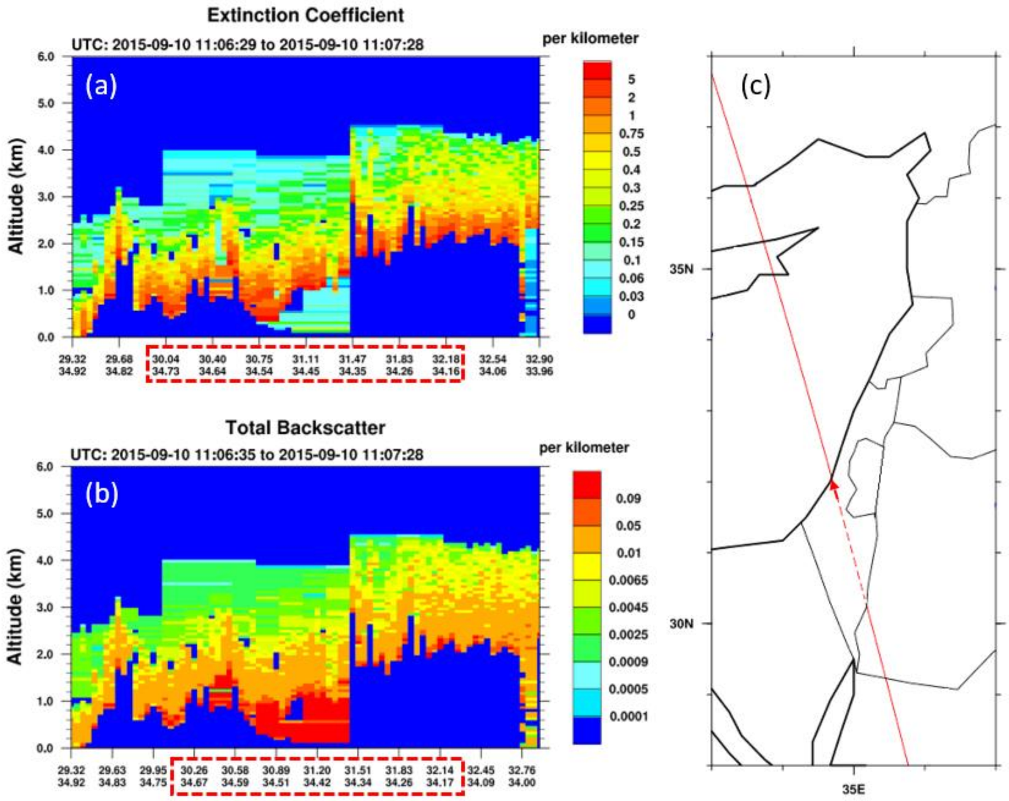


Figure 21. <u>(c) </u>A map of <u>the EM centered on Israel with indication of </u>CALIPSO satellite ~~overpasses (right panel). The only ~~overpass ~~above Israel was~~<u>from south-east to north-west (red line)</u> on 10 September 2015 ~~at ~~11:00-11:10 UTC~~ (indicated by a red line). On the left panel are the ~~<u>. </u>CALIOP lidar products ~~of total backscatter and ~~<u>(from 532 nm wavelength) of </u>extinction coefficient~~. Indications of the overpass~~<u> (a) and total backscatter (b) are given along the path</u> over Israel ~~is given by a black rectangle~~<u>(dashed red line). The ground elevation begins from -20 m ASL in the southeastern point. A quarter of the way through ground level rises up to ~ 600 m ASL and then gradually declines to sea level height as it reached shoreline in the northwestern point</u>.

~~As ~~<u>In the attempt to determine the "end" of </u>the dust storm ~~continues to dissipate ~~over Israel, we analyzed measurements from all instruments ~~regarding~~<u>(Sect. 2) seeking</u> values <u>that were </u>measured prior to the dust storm penetration. ~~While ~~AERONET AOD <u>values </u>(Fig.5~~) ~~<u>), solar radiation measurements (not shown) </u>and satellite imagery from MODIS and SEVIRI (not shown) ~~detect~~<u>indicate</u> clearance of the dust storm on 17 September. ~~PM~~<u>On the other hand, PM values</u> and ceilometer profiles ~~indicate~~<u>indicated</u> the dust storm ended 4 days earlier ~~at~~<u>on</u> 13 September (not shown). ~~This~~<u>The difference between the measurements that include atmospheric layers aloft (satellite imagery, solar radiation and AOD AERONET) compared to measurements limited to the lower atmosphere (PM values and ceilometers)</u>

postulates a scheme of ~~two~~several dust ~~levels~~layers or multiple sources of the dust plumes, which may support similar conclusions from previous studies (Stavros et al, 2016; Mamouri et al, 2016, Gasch et al, 2017).

4. Conclusions

A very severe dust storm struck the EM on September 2015. Previous investigations ~~including~~presented in~~-~~-situ and remote sensing measurements~~ and models~~, discussed the initiation of the dust storm in the Syrian-Iraqi border, aspects of its transport over the EM and the limitations of the models to forecast this unique event~~, and several aspects of its transport over the EM.~~. The analysis concentrated mainly on the upper level of the atmosphere ~~and analyzed~~at specific time segments of the dust storm~~ period~~. The benefit ~~here ~~of this study is the provision of continuous measurements of vertical dust profiles ~~of the dust ~~in the lower part of the troposphere ~~and~~from 8 ceilometer sites. The data presented here can be used as a tool to verify state of the art model simulations and provide a different point of view to the ~~continuous measurements at 8 sites in Israel~~meteorological conditions governing the dust plume advection over the EM.

~~———~~This study confirmed that the dust storm entered Israel on 7 September and showed the gradual downfall of the dust plume from ~1000m ASL on 7 September down to ~400 m ASL on 8 September. The detailed ceilometer profiles and auxiliary instruments enabled to separate the dust storm into ~~two~~separated dust layers (beneath and above 1 km~~) and show a complex dispersion which would have been challenging for meso-scale model simulations.~~). As the dust plume descended towards ground level on 8 September, PM concentration increased in the elevated stations (up to 10,280 µg m^{-3} PM10) and radiation decreased down to ~200 W m^{-2} mainly in the northern region. ~~On 9 September as the dust plume diluted, in spite of the high AOD >3, the global radiation (mainly comprised of diffuse radiation) increased, thus enabling the ground heating and the creation of a late sea breeze circulation (~12 UTC) visible as dust arcs near the coast sites (Tel Aviv, Hadera and Beit Dagan). On 10 September, the dust~~

plume motion continued southwest to Egypt, with indication of a dust layer between 2-4 km measured by CALIPSO overpass. The progress of the dust storm from the Syria-Iraqi border (origin) southwest to Egypt over Israel, continued in two levels. The lower level (up to 1 km ASL) dissipated at 13 September while the level aloft (above 1 km ASL) was observed until 17 September.

On 9 September, in spite of the high AOD (above 3), the global radiation (mainly comprised of diffuse radiation) increased, thus enabling sufficient ground heating for the creation of a late sea breeze front (between 11-12 UTC). The sea breeze circulation generated a narrow dust layer detached from the ground in the coastal region (Tel Aviv, Hadera and Beit Dagan).

On 10 September, the dust plume motion continued southwest to Egypt, indicated by CALIPSO as dust layers up to 5 km. The end of the dust storm over Israel was indicated on 17 September by satellite imagery, solar radiation and AOD AERONET, while measurements limited to the lower atmosphere (PM values and ceilometers) indicated the dust storm ended on 13 September. The difference between the various instruments suggests a scheme of several dust layers or multiple sources of the dust plumes.

To conclude, Ceilometers have been found to be a crucial tool in the study of the September dust storm evolution over Israel. In general, ceilometers provide high resolution data base (temporal and spatial) that broaden the scope of the atmospheric measurements. Fortunately, as worldwide ceilometer deployment expands, ceilometers are realized as an essential tool in the analysis of meteorological phenomena and aerosol transport most valuable in the meso-scale.

5. Data availability

PM10 measurements- Israeli Environmental ministry air quality monthly reports:
~~http://www.svivaaqm.net.~~http://www.svivaaqm.net.

Israeli Environmental ministry air quality monthly reports (in Hebrew):
~~http://www.sviva.gov.il/subjectsEnv/SvivaAir/AirQualityData/NationalAirMonitoing/Pages/AirMoritoringReports.aspx.~~http://www.sviva.gov.il/subjectsEnv/SvivaAir/AirQualityData/NationalAirMonitoing/Pages/AirMoritoringReports.aspx.

Weather reports- Israeli Meteorological Service September monthly report (in Hebrew):
~~http://www.ims.gov.il/IMS/CLIMATE/ClimateSummary/2015/hazesept+2015.htm~~http://www.ims.gov.il/IMS/CLIMATE/ClimateSummary/2015/hazesept+2015.htm

Radiosonde profiles –University of Wyoming:
~~http://weather.uwyo.edu/upperair/sounding.html.~~http://weather.uwyo.edu/upperair/sounding.html.

AERONET data- https://aeronet.gsfc.nasa.gov.

Meteosat Second Generation Spacecraft pictures:
http://nascube.univ-lille1.fr/cgi-bin/NAS3_v2.cgi.
https://www.eumetsat.int/website/home/Images/RealTimeImages/index.html

Ceilometer profiles- the data is owned by governmental offices. The data is not online and provided by request.

Author contribution

Leenes Uzan carried out the research and prepared the manuscript under the careful guidance of Smadar Egert and Pinhas Alpert. The authors declare that they have no conflict of interest.

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Table 1. The publications on the September 2015 dust event

Publications	Title	Main Tool	Main outcome
Pu, B. and Ginoux, P (2016)	The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria	MODIS Terra MODIS Aqua DOD AOD, GFDL-AM3 model	Model underestimation in the EM due to inaccurate soil moisture
Parolari et al. (2016)	Climate, not conflict, explains extreme Middle East dust storm	WRF model	Unusual low level westerly wind spread to the EM, to reversely transport the previously eastward particles back to the EM.
Mamouri et al. (2016)	Extreme dust storm over the eastern Mediterranean in September 2015: satellite, lidar, and surface observations in the Cyprus region	MODIS, EARLINET profiles and PM10	Dust plumes from Syria entered the EM in a double layer structure, pointing to multiple dust sources
~~Stavros~~Solomos et al. (2016)	Remote sensing and modeling analysis of the extreme dust storm hitting Middle East and Eastern Mediterranean in September 2015	RAMS model EARLINET lidar, MSG and CALIPSO.	Low model ability to simulate the event, due to inaccuracies in model physical processes.
Jasim, F.H. (2016)	Investigation of the 6-9 September 2015 Dust Storm over Middle East	Satellite MSG-SEVIRI, Meteoinfo model	Two dust storms simultaneously, from northern Syria and Sinai desert created by two low pressure systems
Gasch et al. (2017)	An analysis of the September 2015 severe dust event in the Eastern Mediterranean	ICON-ART model	An unusual early active Red Sea Trough with meso-scale convective systems generating cold-pool outflows producing the dust storm. Model lacked development of a super critical flow to produce excessive wind speeds

Table 2. Ceilometers locations

Location	Site	Long/Lat	Distance from shoreline (km)	Height (m AGL)
Mount Meron	Northern	33.0/35.4	31	1,150
Ramat David	Northern	32.7/35.2	24	50
Hadera	Onshore	32.5/34.9	3.5	10
Tel Aviv	Onshore	32.1/34.8	0.05	5
Beit Dagan	Inland	32.0/34.8	7.5	33
Weizmann	Inland	31.9/34.8	11.5	60
Nevatim	Southern	31.2/34.9	44	400
Hazerim	Southern	31.2/34.7	70	200

*Ceilometer Weizmann is a CL51

Table 3. Ceilometers configurations

Location	Type	Time resolution(sec)	Height resolution (m)	*Height range (km)
Mount Meron	CL31	16	10	7.7
Ramat David	CL31	16	10	7.7
Hadera	CL31	16	10	7.7
Tel Aviv	CL31	16	10	7.7
Beit Dagan	CL31	15	10	7.7
Weizmann	CL51	16	10	15.4
Nevatim	CL31	16	10	7.7
Hazerim	CL31	16	10	7.7

* Height range dependents on sky conditions and is limited as AOD increases.
* In all ceilometers but in Beit Dagan site, data acquisition was limited to 4.5 km based on the BLview firmware

Table 4. Ceilometer technical information

Location	Type	Engine board	Receiver	Transmitter	Firmware
Beit Dagan	CL31	CLE311	CLR311	CLT311	1.72
Weizmann	CL51	CLE321	CLRE321	CLT521	1.03

Table 5. Hourly maximum concentration of PM2.5, collected from 21 monitoring sites, between 7-10 September 2015. The values are ranked from low (dark green) to high (dark red) values.

				PM2.5 (μg m^{-3})			
No.	Site	Height (m ASL)	Region	7-Sep-15	8-Sep-15	9-Sep-15	10-Sep-15
1	Kefar Masarik	8	North	52	378	389	378
2	Ahuza	280	North	36	743	650	419
3	Newe Shaanan	240	North	43	400	466	525
4	Nesher	90	North	43	564	496	349
5	Kiryat Biyalic	25	North	53	424	703	447
6	Kiryat Binyamin	5	North	40	223	412	256
7	Kiryat Tivon	201	North	47	413	416	300
8	Afula	57	North	44	836	550	405
9	Raanana	54	Coast	38	173	291	229
10	Antolonsky	34	Coast	32	470	626	386
11	Ashdod	25	Coast	36	303	750	332
12	Ironi D	12	Coast	34	424	507	327
13	Tel aviv Central Station	29	Coast	41	716	803	451
14	Ashkelon	25	Coast	61	182	537	119
15	Jerusalem Efrata	749	Mountain	106	2285	434	403
16	Jerusalem Bar Ilan	770	Mountain	107	3063	641	518
17	Gedera	70	South	34	433	683	308
18	Nir Israel	30	South	25	363	638	228
19	Kiryat Gvaram	95	South	42	376	870	300
20	Sede Yoav	105	South	45	323	245	228
21	Negev Mizrahi	577	South	42	1748	526	317

Table 6. Hourly maximum concentration of PM10, collected from 31 monitoring sites, between 7-10 September 2015. The values are ranked from low (dark green) to high (dark red) values.

				PM10 (μg m^{-3})			
No.	Site	Height (m ASL)	Region	7-Sep-15	8-Sep-15	9-Sep-15	10-Sep-15
1	Galil Maaravi	297	North	114	3130	1987	1562
2	Karmelia	215	North	39	1120	1008	765
3	Newe Shaanan	240	North	104	3459	2471	1518
4	Haifa Port	0	North	78	1600	1965	1699
5	Nesher	90	North	117	3265	2746	1270
6	Kiryat Haim	0	North	82	1161	1625	1088
7	Afula	57	North	97	3239	2322	1961
8	Um El Kotof	0	Coast	99	2025	2028	1630
9	Orot Rabin	0	Coast	58	1152	1455	999
10	Barta	0	Coast	112	2540	2345	1612
11	Qysaria	19	Coast	54	1067	2116	1272
12	Rehuvot	70	Coast	88	2236	3045	1257
13	Givataim	0	Coast	112	1909	4014	1484
14	Yad Avner	77	Coast	61	1738	2902	1252
15	Ameil	20	Coast	96	2027	3472	1321
16	Shikun Lamed	17	Coast	51	1701	3244	1097
17	Station	29	Coast	87	1420	2176	998
18	Ashkelon	29	Coast	117	953	1692	551
19	Ariel	546	Mountain	128	2723	1481	1358
20	Jerusalem Efrata	770	Mountain	273	7820	1630	1437
21	Jerusalem Bar Ilan	749	Mountain	181	5588	1191	966
22	Jerusalem Safra	797	Mountain	491	10280	2389	1780
23	Gush Ezion	960	Mountain	310	6230	1679	1119
24	Erez	80	South	44	1000	1000	718
25	Beit Shemesh	350	South	115	2097	1943	1788
26	Carmy Yosef	260	South	85	1047	784	594
27	Modiin	267	South	185	2701	2245	1980
28	Bat Hadar	54	South	65	1342	2563	841
29	Nir Galim	0	South	94	1479	2292	1027
30	Negev Mizrahi	577	South	183	9031	2806	1730
31	Eilat	0	South	275	1867	1592	1684