Dear Editor,

We thank the reviewers for careful reading, and for taking the time to write the constructive reviews which helped us to re-think the concept of the paper, to re-evaluate the observation and to consider even new observations, and to rewrite the paper contents as a whole along all the suggestions by the reviewers. Because of all these changes, it makes no sense to present a revised version with marked text packages (indicating changes).

Before presenting step-by-step answers to the detailed comments, we want to summarize the main points of changes:

- **We changed the title and added new co-authors (modeling partners).**

- **We extended the abstract, more straight forward, more observational findings (numbers), almost no speculations.**

- **We changed the introduction, and now clearly state: what is new, what is the motivation for the paper, and that there will be a second complementary (modeling) paper dealing with this record-breaking dust storm. The first draft of the second paper was distributed in the beginning of August.**

- **This second paper is: Solomos et al., Extreme dust storm over Middle-East and the Eastern Mediterranean in September 2015: Modeling study with RAMS-ICLAMS, to be submitted to ACP.**

- **We provide a long section 2 on instruments and retrieval products, almost two pages instead of one paragraph (given in the submitted first version).**

- **We include new observation (visibility observation at three airports in Cyprus and quality-assured daily mean PM10 observations).**

- **We show radiosonde data and include a few modeling results (of the second paper) to show the failure of the models…. (Figure 4). We explain the failure (cloud and thunderstorm processes are not resolved, and also provide the most likely reasons for the enormous dust mobilizations, probably caused by a haboob and associated density currents and strong downbursts**.

- **We re-arranged the order of figures to make the full presentation and discussion more straight forward and exciting.**

- **We use Nicosia radiosonde temperature and humidity profiles now in the discussion of the 8 September observations including the dust layering.**

Reviewer #1

Our answers in bold

The paper describes an exceptional dust storm over Cyprus. Using lidar data, visibility studies, ground based PM10 measurements and several assumptions it is tried to characterize the event. This should help to improve transport models which – according to the authors – totally failed to predict this outbreak. The paper is clearly structured and easy to understand. It focusses on nothing but the dust storm – thus it is quite short. I did not find any errors.

The paper is now much longer (14 pages of text now vs 6.5 pages of text of the submitted version), includes more observations and discussion about the consistency between the different observations.

I think that the paper can in principle contribute to two aspects: validation of transport models or (optical) characterization of desert dust. In both cases the current version must be improved significantly.

We agree and explain in the introduction how we cover that: One paper on observations, and one (follow-up) paper dealing with the simulations.

According to the manuscript the main motivation is to provide information for the improvement of transport models. However, no strategy how to reach this goal is detailed, not even outlined. Which models are meant (in the introduction the authors mention 'state-of-the-art dust transport models' [plural], but only HYSPLIT is mentioned later)? Are the depolarization ratio and the lidar ratio useful parameters to improve a trans- port model? How can these parameters actually contribute to this goal? Would it be sufficient to determine only the backscatter coefficient and the PM10-concentration to check any improvement of the model? According to Section 3.6 wrong meteorological fields were primarily responsible for the bad forecast (not the numerical description of the microphysics of the model). Is it necessary to estimate the vertical profile of 8. September (this is really vague!) for this purpose or would an agreement for the other days be sufficient to check the improvement of the model? From this point of view I recommend to combine this paper with the 'follow-up'-paper mentioned on page 5 line 25. Then it would be possible to clearly demonstrate the role of the data for the improvement of the model, and to show whether it was successful or not.

We clearly state in the introduction that we will have two papers, the first one (this one) will cover the observations, the second one the simulations and the research of the reasons for the major dust storm and why the forecast models failed. All observations are now discussed in a logic way with a minimum of speculations. However, some speculative assumptions cannot be avoided. They are carefully justified and discussed in section 3.1 and 3.2.

The other aspect – I had expected this when I saw the paper the first time – is to study optical properties of desert dust. Though there are already many similar papers on dust of different deserts and different transport paths (mixing, aging), this paper could potentially be a useful contribution: it comprises the 'standard output' of advanced lidar systems (lidar ratio, depolarization ratio, wavelength-dependent extinction and backscatter coefficients), provided that the accuracy of these parameters will be added. If the source region can clearly be identified this study can be a contribution towards a climatology of optical properties of different deserts.

No, we do not like to follow the idea of the reviewer. We just want to present and document a record-breaking dust storm (based on observations). Such storms are rarely described in the literature (we state that), they may occur ones in 20 years in the Eastern Mediterranean. The second paper will deal with the context of the unusual meteorological conditions that triggered this dust storm. This basic concept we want to present.

A combination of both aspects would certainly be the most attractive solution and together with the improvement of the transport model this paper could be a really interesting scientific study (different from many previous ’dust-papers’) and would fit to ACP.

As mentioned ….., with two papers (one dealing with the observations, one covering the simulation) we now have a good concept.

By the way: it is surprising that more than 80% of the references are from the authors themselves. I am sure that there are more publications on these topics.

We increased the list of references as a whole significantly and decreased the percentage of self-citations.

A few minor comments:

• 1-12: ’hit’ change to ’hits’

changed

• 2-14: What is CUT-TEPAK?

Is now explained in section 2.1. Cyprus University of Technology… and then in Greek TEchologiko PAnepistimio Kyprou.

• 3-10: ’observations from pilots’: where is this information actually coming from? What exactly do they provide?

This information is removed, now we show measured visibilities.

• 3-16: Is this from the Koschmider’s formula?

Yes, it is! We now provide much more explanations in an extra subsection 2.4 on visibility measurements.

• 3-22: ’are not validated’: What does this mean? What errors can be expected? Would it have been possible to validated these data (under which conditions)?

Removed

• 4-6: ’AOT close to 1’: where is this estimate coming from?

Changed, or better removed. It was estimated from the lidar observations.

• 5-8: ’The technique applied ... is described’: This should be briefly outlined here so that the reader immediately can understand which measurements and which assumptions are used.

We extended significantly the description of the observational methods in section 2. We introduced subsections 2.1-2.4. We provide many references and provide uncertainty discussions.

• 5-10: typo: ’extreme’

Changed

• Fig. 7: I would expect that the curves in Fig. 7 (dust concentration) are proportional to the backscatter profiles shown in Fig. 6. At least for 10. September this seems not to be the case. This emphasizes the need to better explain the way how the mass concentration is determined (see previous comment).

All profiles are ok. The old figure 7 (now figure 9) shows the pure dust mass profiles, whereas the profiles in old Figure 6 (now figure 8) showed the total aerosol backscatter profiles (dust plus non-dust components)

Reviewer #2

Extreme dust storm over the eastern Mediterranean in September 2015: Lidar vertical profiling of desert dust at Limassol, Cyprus.

1 General comments

This article describes an exceptional dust event observed in Cyprus. The authors combined remote sensing from ground and space with ground-based in-situ aerosol measurements and models to give a comprehensive overview of the dust plume. The paper is rather descriptive, but the described methods are sound and the data set is unique. Therefore, I would recommend the paper to be published in ACP. However, there are some fundamental points that need to be addressed before publication. My specific comments and technical corrections are given below.

The paper deals with a record-breaking dust storm that may take place ones in 20 years. We bring together many state-of-the-art observations including excellent Raman/polarization lidar observations. So all this unique, and should be enough to justify publication. Of course we got the message, and improved the introduction to provide a proper motivation for this paper (discussion of observations) and that there will be a second paper dealing with modeling of this event.

2 Specific comments

Both, introduction and conclusions, should be reworked. The introduction is giving results described later in the text, which is not appropriate. Besides, in a rather short and straightforward paper like this, a detailed description of the structure of the paper is not necessary. I would suggest to present a stronger, more concise motivation. Also, the state of knowledge on Middle East dust is not discussed and should be included.

Yes, we agree, and improved the introduction and conclusion sections accordingly. However, we leave out to discuss the state of knowledge of Middle East dust.

The conclusions are rather a summary of the results. One of the review criteria for publication in ACP is the following: "Are substantial conclusions reached?" Please consider this point, which is the main weakness of this manuscript in my opinion.

We got the message and improved the introduction and conclusions.

What I'm also missing are information on the difference between local time and UTC. Besides, it would be very beneficial to include more details on the model forecast. The failure of the model is mentioned a few times, but what was actually forecasted?

Is now given in Figure 1, caption (EEST: Eastern European Summer Time, three hours in front of UTC), and also repeated in the text.

Some more detailed comments:

page 1, line 3 Please include a better discussion about the models failing to predict the event in the main text. You highlight it in the abstract and it is repeated in the main text, but it is not shown.

Is now given in the Introduction.

introduction The first paragraph of the introduction is a summary of results. Please remove. Also I'm missing some lines motivating this study. It is remarkable, but why is it important to study such cases in detail? Please also discuss literature on Middle East dust.

We improve the Introduction as a whole, provide motivating points for reporting this record-breaking dust storm, stating our two-paper concept, providing literature hints on aerosol climatologies in the Mediterranean, etc.…

page 2, line 2 replace "accurately determined" by "estimated"; I don't think an estimation "around 500 m, but clearly below 750 m" should be called accurate.

We changed the text accordingly. We estimate the visibility now to be 500-600m.

page 2, line 4 Also here I have some concerns about the "good accuracy". You don't give uncertainties in your estimate, but a range of values. Which is ok, but a range of 3000 µg/m3 should not be called accurate. You present a simple and very nice method to estimate the dust load, but the emphasis here is on "estimate". It is not a precise measurement and should not be presented as such.

We agree and changed wording.

page 2, line 10 Why were data at 1064 nm not used for the dust characterisation, for example to calculate the Ångström exponent (only for time-height plots, figure 5)?

We tried, but the result was not reasonable, we speculate that the photon-detecting APD prohibits a good retrieval 1064nm backscatter signals.

page 2, line 12 Which of the cited publications describe the set-up used for this work?

We extended the instrument descriptions in Section 2. Provide now detailed information in four subsections and detailed references for the methods and product uncertainties.

page 2, line 13 Which of the cited publications describe the data analysis used in this study? It would be helpful to at least give the main points of the analysis and specify which reference describes what.

As just mentioned, we do it now in a better way.

page 3, lines 17-18 Could you please discuss the influence of humidity and consequent hygroscopic growth of the dust particles on the dust mass concentration?

Yes we do that now in the result section 3.2. But the relative humidity was at all below 50% so there is no water uptake effect, and then we have dust which is quite hydrophobic.

page 4, line 12 I would interpret "morning" and "noon" as indicators of local time. But either way, 14:20 is afternoon. It's a small detail, but can be confusing if you are not familiar with the time zone of Cyprus. Rather be specific.

Local noon is 12 local time.

We provide now local time information at several places (EEST).

figure 6, caption How did you obtain the uncertainties?

We give this information now in Section 2.1. There, we provide references to the retrieval methods and the uncertainty estimations. We obtain the errors by assuming the error propagating law.

page 5, line 10 A "front" is a distinct line (or surface); the front of the plume. The passage of it should not take three days. I suggest you rephrase by replacing "dust front" by "dust plume" or similar.

We are now careful with wording.

page 5, line 13 Who defined this threshold? And why?

The statement is removed.

page 5, line 20 Predicted by which model(s)? What did it/they predict for 35◦? And for 33◦?
conclusion It is a summary rather than conclusions. Try to make a stronger case for your findings. What is the contribution of this work to existing knowledge? And how does it link back to your motivation?

We improved the Introduction and the conclusions, give better motivation, give real conclusions. Not just summary of the paper, and say that we will have a second paper, focusing on modeling of this event.

3 Technical corrections

All of the following remarks were considered before we started to rewrite the entire paper, section by section

page 1, line 20 replace "re-analyze" by "re-analyzing"

page 1, line 24 replace "imaginary" by "imagery"

instrumentation I suggest to rename this section to "Instrumentation and methodology".

page 2, line 18 replace "imaginary" by "imagery"

page 2, line 20 replace "dust plumes were partly" by "parts of the dust plumes were"

figure 2 Why are there two dots at the same location each day? Are those from MODIS on Aqua and on Terra, respectively? Please specify this in the text or caption.

Yes, from MODIS on AQUA and TERRA. We state that now in the respective figure (new figure 6).

figure 5, caption In my opinion the following part of the caption should be included in the main text body as part of the discussion of the figure: "The signals backscattered by dust in the elevated layers above 1000-1500 m height are partly strongly attenuated by the desert particles occurring below 1500 m. As a consequence, the elevated layers are mostly given in blue and green instead of red (as it would be the case after the correction of the attenuation effect)."

Done

page 3, line 31 Please include lines 3 and 4 from page 4 (starting with "Unfortunately, ..." ending with "... detection units.") after the sentence ending with "... the highest dust load.".

page 3, line 31 I don’t think it is obvious, as you don’t show lidar profiles from that day.
You could rephrase this sentence, e.g. "Judging from the MODIS observations in Fig. 1., the rather thick dust layer reached 1000-1500 m height on 8 September."

We now include radiosonde information of 8 September. These data perfectly corroborate our ‘speculation’. So, there was definitely a 1.5 km thick and well-mixed layer (with base at surface on 8 Sep, noon) causing this optical depth of 6-9. In this

estimation of AOT we take the estimate of the surface extinction coefficient to 6000 Mm-1 and assume a 1.5 km thick well-mixed layer. That's it. And we end up with an AOD of 9. Lidar and radiosonde data are in perfect harmony for the entire period from 7 to 11 September. This motivated us to use the radiosonde profiles alone to estimate the layering on 8 September. We find, this is fully justified. So, we do now use the 8 September temperature and humidity profiles to explain the dust layering and that the dust was well mixed from the ground up to 1500 m height (as inidcated by the humidity profiles on 8 Sep) and caused and optical depth of 6-9. All this is now discussed in Section 3.2.

page 4, line 12 replace "session" by "sessions"

page 4, line 19 replace "is" by "was"

figure 6 Please change the labelling on the x-axis of the depolarisation ratio plot.
It is hard to tell the numbers apart. You could leave major ticks at 0.2 and 0.4 (with labels) and use minor ticks at 0.1 and 0.3 (without labels).

Done

figure 6, caption The following parts should be included in the main text body rather than the caption: "The Raman lidar method is applied.", and " Retrieval uncertainties are of the order of 10% (backscatter coefficient, depolariza- tion ratio), 25% (extinction coefficient), and 30% (lidar ratio)."

Since we avoid to show error bars to make the figures not too busy, we left the information about uncertainties in the captions (but also explain that in the text).

figure 6, caption Add reference to "Raman lidar method". [now in text body]

page 5, line 10 replace "extrem" by "extreme"
page 5, line 15 Please specify length of trajectories in days in the text. It is in my opinion not enough to include it in the caption of figure 8.
page 5, line 19 replace "dust advection" by "air mass transport"
figure 7, caption Please move the following part of the caption to the main text body: "A dust particle mass density of 2.6 g/cm3 is assumed in the retrieval. The overall uncertainty is 30% and mainly caused by the uncertainty in the dust volume-to-extinction ratio (extinction-to-volume conversion factor)
assumed to be $0.8 * 10^{-6}$ m."
figure 7, caption Add references for the mass density, conversion factor and uncertainty estimation. [now in text body]

Reviewer #3:

Review of the paper "Extreme dust storm over the eastern Mediterranean in September 2015: Lidar vertical profiling of desert dust at Limassol, Cyprus" by Mamouri et al. submitted to Atmospheric Chemistry and Physics.

This short paper describes the case of an extreme dust plume occurred over Eastern Mediterranean lasting for few days and observed with ground based measurements at Cyprus. In addition satellite products from MODIS are used. The paper is within the scopes of Atmospheric Chemistry and Physics as it presents a rare (may be unique) dust event. However, in its current version needs major revision before it can be accepted for publication. The two main reasons is the lack of uncertainties throughout the paper and the presentation of speculative results (although not necessarily wrong) in the aim to characterize the event especially for the 8th September when lidar data were not available. For more details see the comments below

Major comments

1) Cyprus has four WMO stations (https://www.wmo.int/cpdb/dashboard/index/countryCode:CYP). Why you do not present visibility results from them? At least 3 (Akrotiri, Larnaka, and Paphos) of them take visibility observations, with Akrotiri being next to Limassol (~25 km). The data should be available at least through the national meteorological service of Cyprus. Although, the photographs in Figure 3 are indicative of the low visibility occurred during the noon of 8th and the contrast with 9th September, still they do not follow exactly the WMO guidelines especially when visibility is poor, as established in WMO Guide to Meteorological Instruments and Methods of Observation (http://library.wmo.int/pmb_ged/wmo_8_en-2012.pdf). The visibility results will permit also an assessment of the variability of the dust extinction-to-mass conversion factor given the observations of PM10 for the 3 sites providing both types of observations.

Thank you for hint! We now show the visibility observations from the three airports mentioned above (new Figure 7). However, to analyze photos with a lot of buildings is to our opinion much more accurate than to estimate visibility at very unusual dusty conditions! And later, when we compare the visibility-based mass concentrations with PM10 values, we clearly get the impression that the airport visibility estimates are quite erroneous (by a factor of 2 too low visibilities) for 8 September. We discuss this in section 3.2).

2) For a short paper like this presenting an extreme event, what I was hoping to find was uncertainties to all the observations and of course the factors used from previous studies. Just providing mean values is not enough in order to establish the importance and the uniqueness of this event, especially for the values mentioned in the abstract and conclusions. Although, the authors provide estimations in the legends of Figures 6 and 7, it would be better to introduce them in the manuscript and the figures. While there are not uncertainties presented regarding the results of 8th September.

We expanded the instrumentation section 2, now with four sub-sections, and provide many references to the techniques and the uncertainties, and provide a good overview of all the uncertainties. We do not show error bars in the figures (now 8 and 9) to avoid overloading. We prefer to provide uncertainty information in the captions.

3) In the abstract and the conclusions you present mass concentrations values esti- mated from visibility by using a typical dust extinction-to-mass conversion factor. Also, the AOD values of 6-10 are based on assumptions about the vertical distribution. Although, in both cases the values are logical (according to the analysis presented in Section 3), simply they are not measured, so I strongly suggest to present in the abstract and the conclusions only the observations by adding the phrase “with possibly higher values occurred the 8th

September" or something similar. Especially, in the case of mass concentration there are measurements and PM10 (or PM2.5) is what you find in the literature. For this reason is more appropriate to present the PM10 measurements in the abstract/conclusions.

We changed the abstract accordingly, and removed speculative values.

4) The Introduction needs rewriting, especially paragraphs 1 and 3. What's the point to present the results of the study already in the Introduction section in a short paper like this? On the other hand, there is no reference at all about climatological and extreme event studies for the region. At least, there are studies covering the Eastern Mediterranean dealing with AOD, lidar measurements and PM10. Example of relevant papers (certainly a non exhaustive list) can be found below:

Basart, S., Pérez, C., Cuevas, E., Baldasano, J. M., and Gobbi, G. P.: Aerosol characterization in Northern Africa, Northeastern Atlantic, Mediterranean Basin and Middle East from direct-sun AERONET observations, Atmos. Chem. Phys., 9, 8265-8282, doi:10.5194/acp-9-8265-2009, 2009.

Gkikas, A., Hatzianastassiou, N., and Mihalopoulos, N.: Aerosol events in the broader Mediterranean basin based on 7-year (2000–2007) MODIS C005 data, Ann. Geophys., 27, 3509-3522, doi:10.5194/angeo-27-3509-2009, 2009.

Gkikas, A., Hatzianastassiou, N., Mihalopoulos, N., Katsoulis, V., Kazadzis, S., Pey, J., Querol, X., and Torres, O.: The regime of intense desert dust episodes in the Mediterranean based on contemporary satellite observations and ground measurements, At- mos. Chem. Phys., 13, 12135-12154, doi:10.5194/acp-13-12135-2013, 2013.

Papayannis, A., et al. (2008), Systematic lidar observations of Saharan dust over Europe in the frame of EARLINET (2000 – 2002), J. Geophys. Res., 113, D10204, doi:10.1029/2007JD009028.

Querol, X., Pey, J., Pandolfi, M., Alastuey, A., Cusack, M., Pérez, N., Moreno, T., Viana, N., Mihalopoulos, N., Kallos, G. And Kleanthous, S.: African dust contributions to mean ambient PM10 mass-levels across the Mediterranean basin, Atmos. Environ., 43, 4266–4277, 2009.

The authors should review the literature in order to establish the extreme character of the event.

The introduction is completely re-written. As mentioned above, the introduction now contains the motivation of the paper, the hint that there will be second modeling paper, and we provide a few references on aerosol conditions over the Eastern Mediterranean, and give definitions of strong and extreme dust outbreaks. And an outbreak causing an optical depth of 0.8 is already an extreme dust outbreak, and we had 6-9!...which may happen once in 20 years…

More specific comments regarding the Introduction follow:

i) Page 1, Lines 11-14: "The visibility ... 10000 µg/m3." If I understand these are the results of the paper. If not provide the reference otherwise delete the sentence.

All this re-written and presented in a clear way. The link between visibility and extinction is well known,,, and between extinction and volume or mass concentration is also not new and describe in section 2.1. now explicitly.

ii) Page 1, Lines 14-15: Some thing as previously if there is a reference, please provide it otherwise delete.

We changed it.

iii) Page 1, Lines 16-17: “Surprisingly ... models.” Please provide information about the models. E.g. http://sds-was.aemet.es/?

We change it in the introduction accordingly and provide the link to the sds-was web page.

iv) Page 1, Line 23 to Page 2, Line 7: How useful is to provide this breakdown of Section 3 in a short paper? The authors repeat themselves several times. I suggest deleting it and incorporating any additional information provided in this part (if any) to the relevant subsections.

As mentioned we re-wrote the entire paper….

5) Page 2, Lines 14-15: Although, there are not observations from the CUT- TEPAK AERONET sun-photometer during the event, there are observations (at least Level 1.5) from other sun-photometers in the region like AgiaMarina_Xyliatou and SEDE_BOKER. It is important to compare MODIS AOD retrievals with AERONET values in order to establish how good there are in the case of large AODs (>2). This is important, especially, from the moment that you are using MODIS AOD over Cyprus in Section 3.1.

We try to compare the MODIS observations with our own lidar observations (section 3.2). We do not include other stations. The dust outbreak was so inhomogeneous, what does it help to include other stations? The uncertainty of MODIS values is clear, about 0.15 times AOT.

Minor comments

6) Page 1, Lines 2-3: Which dust models, give details otherwise delete.

All of them! This is now better stated in the introduction, pointing to the sds-was web page.

7) Page 2, Line 19: Add reference for MODIS AOD.

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F., and

Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech., 6, 2989-3034, doi:10.5194/amt-6-2989-2013, 2013.

Thank you, we now include Levy, 2013 and also one of 2010. We provide information on the uncertainty in section 2.2, is about 0.15 AOT.

8) Page 2, Lines 26-30 and Page 3, Lines 19-26: The authors present AOD and PM10 observations for several sites in Cyprus, but they do not discuss the differences between them, i.e. the spatially variability. Either discuss the spatial variability among the different sites or just present the data for Limassol. In the former case, I suggest to present the MODIS AOD maps (similar to Figure 1) instead of the AOD time series, probably zooming in Cyprus. Otherwise use the same time range and the same cities for Figures 2 and 4.

We kept these good suggestions in mind and changed the presentation now. We combined the old Figures 2 and 4 to the new Figure 6. But we prefer numbers and time series here, even if they were clearly biased on 8 September (when AOT was higher than 5).

9) Page 3, Lines 9-11: Provide reference for the visibilities obtained from pilots.

We removed this. We just found it in the internet. Now we have visibility observations, that is better solution.

10) Page 3, Line 23: "... and thus main contain errors." Ask the Air Quality Department of Cyprus for validated data. Otherwise, what's the point of presenting data in your manuscript which are of unknown quality?

Yes, we did, but asked us (how good are these data during such an extreme dust event…). Every observation is somehow optimized to work well at usual and up to some extreme conditions. But here at these rather unusual conditions? We do not really believe in any (validated or not validated) in situ observation. Furthermore, the only validated data that DLI provides are daily mean values, following the EU guidelines. We used the hourly means at 4 DLI stations to highlight the spatial-temporal variability and the density of the event. Nevertheless we discuss the deviations between the validated daily means and the daily means calculated from the non-validated hourly means and found deviations of 50%. That is discussed now in section 2.3.

11) Page 3, Line 30: Replace "Cyprus" with "Limassol", as the lidar observations are from Limassol and as you stated in Page 2, Lines 23-25 the Troodos Mountains were always visible during the dust storm, certainly not affected the same way with Limassol.

We made the discussion more save… (sections 3.1 and 3.2)

12) Page 3, Line 30: "A two-layer structure ... on 8 September," this is pure speculation. Either present observations or delete it.

As already given above, we now include radiosonde information of 8 September. These data perfectly corroborate our 'speculation'. So, there was definitely a 1.5 km thick and well-mixed layer (with base at surface on 8 Sep, noon). And by using the visibility-related extinction coefficient of 6000 Mm-1 we end up with an optical depth of 9. All in all, lidar and radiosonde data are in perfect harmony for the entire period from 7 to 11 September. This motivated us to use the radiosonde profiles alone to estimate the layering on 8 September. We find, this is fully justified. So, we do now

use the 8 September temperature and humidity profiles to explain the dust layering and that the dust was well mixed from the ground up to 1500 m height (as inidcated by the humidity profiles on 8 Sep) and caused and optical depth of 6-9. All this is now discussed in Section 3.2.

13) Page 4, Lines 5-7: This is just a speculation, as you do not have any information about the vertical distribution of the dust. The authors should underline more this fact using a stronger word than assumption. The fact that the Troodos Mountains were not covered by dust means that possibly the dust layer was below 2 km, but it could be just 500 m (or lower) like the 9th September (Figure 5). On the other hand, Figure 6 shows through the backscatter coefficient that the layer was not homogeneous with the higher values at surface during the 9th September, so this could be the case for the 8th. At this point MODIS maps can give a hint about the area with the high AOD (even saturated at 5), while also the AOD observations from MODIS/Terra could be useful to check the temporal variability. Certainly, this result although plausible can not be one of the main conclusions of the paper as it is based on assumptions which can not be verified. Instead the authors could use the MODIS AOD.

As mentioned, we now include radiosonde information of 8 September….. These data indicate a well-mixed 1.5 km thick lower dust layer. And with surface extinction coefficients of 4000-6000 Mm-1 we end up with AOT of 6-9. And this also in agreement with MODIS. MODIS stops when the AOT is largere than 5. And there are many MODIS pixels (areas) with higher AOT than 5, as discussed in section 3.2. MODIS does not provide data higher than 5. We use MODIS TERRA and AQUA data and do not see strong temporal variability…

14) Page 4, Line 19: The word frequently is in contrast with just one case study mentioned in the next sentence. Either rephrase or use another reference for the altitude of Saharan dust plumes over Cyprus.

We changed it

15) Page 4, Line 24: Why you do not use the same time interval, e.g. 18-20 UTC for all profiles shown in Figures 6, 7? Although, I do not expect large changes in the results (if any) the comparison between the four days will become straightforward.

The lidar is not that powerful, so we need long signal averaging times. And if we have the chance to use longer time periods (with comparably homogeneous aerosol conditions) we should take the opportunity. So, we leave Figure 8 and 9 (old figures 6 and 7) as they were…. regarding signal averaging time intervals.

16) Page 5, Lines 1-4 and Figure 6: For all four days the depolarization ratio reduces significantly below about 0.5 km. This means that surface aerosols are always a mix- ture of dust with pollution or is just an instrument artefact e.g. overlap function?

The depolarization profiles are fine, and show the pollution impact . We discuss that at the end of Section 3.2 (based on numbers for mass concentrations).

17) Section 3.6 and Figure 8: I do not think that this section and figure add something in the paper. I suggest to totally removing both. Otherwise, the authors should justify their utility.

We removed all this (a bit), but want to show at least one HYSPLIT result so that the reader get at least a rough idea about the air mass transport from the Middle East on these days…

Technical comments 18) Page 1, Line 24 and Page 2, Line 18: Replace 'imaginary' by 'imagery'.

Done

Reviewer #4:

This brief study presents lidar measurements acquired during an extreme dust storm which swept across the Middle East in September 2015. The lidar observations are high quality and are fascinating. I have no particular issues with the data process- ing etc... However, I think that the scientific content of the paper is weak. I do not recommend publication in ACP, for the reasons detailed below.

I believe the paper would be a better match for AMT.

This is a surprising statement! … and we do not agree.

To our understanding, ACP is the journal for presenting scientific results which includes atmospheric observations. AMT is the journal for presenting new techniques and new instruments. And we present observations.

General Comments

1. In particular, I am missing an analysis of the synoptic situation leading to the dust storm, and how this situation evolved and led to the demise of the dust storm as observed with MODIS and the lidar in Limasol. I am also missing a detailed analysis of the processes leading to the dust emission and transport, as well as the activated source regions. In several instances, the authors state that dust transport models failed to predict this record dust event, without giving precision on the models, their resolution, etc. . . An analysis of such processes would be extremely useful to understand why the transport models did fail, if they did.

As now outlined in detail in the abstract (already) and in the introduction, we will have a series of two paper: part one (this paper) on observations and part two (all the modeling aspects). In the second paper, the meteorological conditions will be discussed and the specific reasons for this huge dust storm will be outlined. However, we give a short meteorological explanation already in the introduction of this paper and then in section 3.2.

2. I also find the interpretation of the HYSPLIT back trajectories to lack insightful analysis. The authors find them to be in contradiction with their dust observations, and ascribe the differences to erroneous meteorological fields provided by global scale models. This may well be the case but the main issue is that HYSPLIT cannot not deal with turbulence and transport in turbulent planetary boundary layers (PBLs). However, this is not verified in the

present study and one wonders what is the worth of including these back trajectories in the analysis (?).

The HYSPLIT trajectories are not very useful, we agree. Nevertheless, we show one HYSPLIT plot to provide a rough idea about the main features of dust transport and some hints on dust sources.

3. Emphasis is put in the abstract on the supposedly large AOD and mass concentra- tion during the event. However, these values are not observed on 8 September (the day when the storm was most intense), and are only speculative, extrapolated from indirect measurements, or based on assumptions. They can be discussed in the text, but should not be emphasized that much in the Abstract and in the conclusion (where they are presented as results, see p5, l 28: "Dust AOT values of the order of 6-10 oc- curred over Cyprus [. . .]"). Furthermore, the very large AOD values (6-10) inferred on that day from pseudo-lidar measurements and yet MODIS retrievals on the same day are thought to be biased (p2, l30).

We removed speculative values from the abstract and the conclusions (completely re-written).

As mentioned already above, we now include radiosonde information of 8 September. These data perfectly corroborate our 'speculation'. So, there was definitely a 1.5 km thick well-mixed layer from the ground to 1.5 km height. And when we use the visibility of 500m and therefore extinction coefficients of 6000 Mm-1 then we simply have to conclude that the AOT was 9 (for 4000 Mm-1 we get an AOT of 6). Lidar and radiosonde data are in perfect harmony for the entire period from 7 to 11 September. So, we do not see any reason not to use the 8 September radiosonde temperature and humidity profiles (alone) to explain the dust layering on 8 September. All this is now discussed in a reasonable and consistent way in section 3.2.

4. The 2-layer structure observed by lidar on 7 September suggests different emission source regions and transport regimes from Middle East, as is the case in other parts of the world, like the Sahara. This structure likely relates to differential advection and PBL dynamics over the emission regions. Knowledge of these processes would be extremely useful for a comprehensive analysis of the back trajectories.

Yes, the two-layer structure indicates different dust sources and different transport regimes. More insight into the basic meteorological processes are given in the follow-up modeling paper (part 2, simulations).

Minor comments

P1, l 14: where does the number 1000 μg m-3 come from?

The Introduction is completely rewritten, the statement is removed.

P1, l 17: which models do you refer to?

All models failed. We now provide the internet link to the sds-was.aemet.es web page, where you can see that.

P1, l 24: imagery

Improved.

P2, l20: [. . .] we in some parts so dense [. . .]

Changed

P2, l 24-25: yet you show later on that dust plumes were observed by lidar above that height. . . Does this mean that the dust plume transported at higher altitude was less optically thick?

Yes the second layer shows AOTs of 0.5 on 7 and 9-10 September.

P2, l 30: why are they biased?

We averaged numbers <5.0 (good and validated observations) and many values of 5.0 (not observed, but just set to 5.0, although the true values were much higher…). Then we averaged all these numbers….

P3, l 24-26: how do you know particles bigger that 10 μm are transported to Cyprus? Furthermore, what is the influence of marine aerosols on these measurements? Would not they influence the surface mass concentration measurements (Limasol is close to the sea)?

We changed the text. Provide a discussion. Kandler et al. (2009, 2011) clearly shows that total dust mass concentration is always larger (by a factor of 1.2-1.8 after long-range transport) than the PM10 mass concentration. We corroborate that with our study (and mention that in section 3.2) So, there are larger particles. We also discuss the negligible impact of marine and urban particles in the case of a huge dust storm.

P3, section 3.3: in this section, nothing is said about the high backscatter values observed in the lower layer (island or marine PBL?). Do not you expect dust to also be present in the lower layers as the result of entrainment at the top of the PBL?

We discuss that now, too (at the end of section 3.2). Yes, there is always pollution aerosol besides dust aerosol at low heights….and yes, there is dust at surface level…

P3, l30: regarding the 2 layer structure: you do not have lidar data, but do you have met soundings to show the suggested layering?

Thank you for the hint. We plotted all available Nicosia radiosonde profiles of temperature and humidity, we found nice agreement between aerosol layering and temperature and humidity gradient changes…, text book like. And these features seen for all lidar measurement days (7, 9-11 September) corroborate our conclusions on the layering on 8 September. The two-layer structure was there all the time. The lowest layer was well mixed on 8 Sep. from the surface up to 1.5 km height. According to the visibility study on 8 September the dust mass concentration was extremely high and caused AOTs of 6-9. All this is given in the discussion in section 3.1 and 3.2.

Extreme dust storm over the eastern Mediterranean in September 2015: Satellite, lidar, and surface observations in the Cyprus region

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Abstract. A record-breaking dust storm originating from desert regions in northern Syria and Iraq occurred over the Eastern Mediterranean in September 2015. In this contribution of a series of two articles (part 1, observations, part 2, atmospheric modeling), we provide a comprehensive overview about the aerosol conditions during this extreme dust outbreak in the Cyprus region based on satellite observations (MODIS, aerosol optical thickness AOT, Ångström exponent), surface particle mass (PM_{10}) concentrations measured at four sites in Cyprus, visibility observations at three airports in southern Cyprus and corresponding conversion products (particle extinction coefficient, dust mass concentrations), and EARLINET lidar observations of dust vertical layering over Limassol, particle optical properties (backscatter, extinction, lidar ratio, linear depolarization ratio), and derived profiles of dust mass concentrations. Maximum 550 nm AOT was clearly $>$5 and correspondingly the mass loads were probably $>$10 g/m^2 over Larnaca and Limassol during the passage of an extremely dense dust front on 8 September 2015. Hourly mean PM_{10} values were close 8000 μg/m^3, the observed meteorological optical range (visibility) reduced to 300–750 m at Larnaca and Limassol. The visibility observations suggest peak values of the near-surface total-suspended-particle (TSP) extinction coefficients of 6000 Mm^{-1} and thus TSP mass concentrations of 10000 μg/m^3. The Raman/polarization lidar observations showed a two–layer structure of the dust plumes (reaching to about 4 km height), pointing to at least two different dust source regions. Dust particle extinction coefficients (532 nm) exceeded 1000 Mm^{-1} and the mass concentrations reached 2000 μg/m^3, respectively, in the elevated dust layers on 7 September, more than 12 hours before the peak dust front on 8 September reached the Limassol lidar station around local noon. Typical Middle East dust lidar ratios around 40 sr were observed in the dense dust plumes. The particle depolarization ratio decreased from around 0.3 in the lofted dust layers towards 0.2 at the end of the dust period (11 September) indicating an increasing impact of anthropogenic haze.

1 Introduction

On 7–11 September 2015, a record-breaking dust storm hit Cyprus. The visibility decreased to 300–500 m for more than 12 hours at Larnaca International Airport on 8 September, and the maximum aerosol optical thickness (AOT) exceeded $>$5 at 500 nm over eastern and southern Cyprus. The dense dust clouds with peak mass concentrations of the order of 10 mg/m^3

originated from Middle East deserts, mainly from northeastern Syria and northern Iraq. According to a recently presented climatology of strong and extreme dust events over the Mediterranean Sea (Gkikas et al., 2016), based on satellite observations from 2000–2013, extreme dust events, characterized by an AOT exceeding the climatological mean AOT by four standard deviations, occur, on average, 1-2 per year for a given site. In fact, eight extreme dust outbreaks (with AOT>0.75 at 500 nm) were observed at the Aerosol Robotic Network (AERONET) station at Limassol, Cyprus, in the Eastern Mediterranean in the time period from June 2011 to June 2015. However, extreme events with AOT>4.0 to 5.0 as in September 2015 are rather seldom and may occur once in a decade. An extended aerosol characteristics for the Mediterranean region, including statistics on strong dust events and an extended literature survey is given by Georgoulias et al. (2016).

Dust transport models widely failed to predict this record-breaking dust storm (http://sds-was.aemet.es/forecast-products/dust-forecasts/compared-dust-forecasts). This fact and the enormous dust mass concentrations measured in Cyprus motivated us to investigate the underlying weather conditions that caused this huge dust outbreak. Extreme dust events provide a unique opportunity to learn more about known and established dust mobilizing mechanisms and to identify and explore even new or not well parameterized dust emission processes. The dust storm was obviously linked to an extraordinary weather situation with dust mobilization features on scales which were too small to be resolved by the used global and regional weather and dust transport models. We investigate this extreme dust event in detail by combining the available dust observations in the Cyprus area (presented in this article) with complex atmospheric modeling (presented in the second paper, Solomos et al., Extreme dust storm over Middle-East and the eastern Mediterranean in September 2015: Modeling study with RAMS-ICLAMS, to be submitted to ACP). The occurrence of a haboob in northeastern Syria and northern Iraq was probably responsible for this unique dust outbreak. Haboobs are intense dust storms caused by strong thunderstorm activity, which are associated with density currents (Knippertz et al., 2007; Solomos et al., 2012), strong precipitation and vigorous cold-air downbursts reaching the ground and pushing huge amounts of dust and sand into the air.

The goal of this first article is to provide an overview of the available dust observations in the Cyprus region. We present time series of spaceborne observations (MODIS, Moderate Resolution Imaging Spectroradiometer) of aerosol optical thickness (AOT) for five sites in Cyprus, continuous particle mass concentration measurements (PM_{10}, mass concentration of particles with aerodynamic diameter smaller than 10 μm) at four stations, visibility observations from three airports in Cyprus, and lidar observations, performed at Limassol. We are not aware of any report in the literature in which a severe, record-breaking dust storm has been discussed in so much observational detail. The lidar measurements are especially highlighted in our study. The observed temporally and vertically resolved dust layering structures and the derived profiles of particle extinction coefficient and dust mass concentration provide indispensable information for dust transport simulation studies (presented in the second article). Comparison of modeled and lidar-derived dust profiles are of basic importance in model-based investigations of the relationship between given meteorological conditions over the dust source regions, dust mobilization, and observed long-range dust transport features (Heinold et al., 2009, 2011; Müller et al., 2009).

Several long-term lidar studies of dust outbreaks towards the Mediterranean are available, however with main focus on Saharan dust outbreaks (e.g. Amiridis et al., 2005; Mona et al., 2006, 2014; Papayannis et al., 2008; Papayannis et al., 2009). An extreme Saharan dust event with AOT up to 1.5 at 500 nm over southern Spain observed with lidar was discussed by

Guerrero-Rascado et al. (2009). A first lidar-based long-term study for the Eastern Mediterranean which includes Saharan as well as Middle East desert dust outbreaks has been presented by Nisantzi et al. (2015), based on the Limassol lidar observations.

After the introduction, a brief description of the observation methods, data analysis, and measurement products is given in Sect. 2. The observations are presented and in Sect. 3. A few concluding remarks are given in Sect. 4.

2 Aerosol instrumentation and observational products

2.1 EARLINET lidar profiling of dust optical properties and mass concentration

The lidar observations were conducted by the Cyprus University of Technology (CUT), at Limassol (34.7°N, 33°E, 23 m above sea level), Cyprus. The lidar station belongs to the European Aerosol Research Lidar Network (EARLINET) (Pappalardo et al., 2014) and is equipped with a 532 nm polarization/Raman lidar (nitrogen Raman channel at 607 nm)(Mamouri et al., 2013; Mamouri and Ansmann, 2014; Nisantzi et al., 2015). The EARLINET site is combined with an Aerosol Robotic Network (AERONET) station (Holben et al., 1998; Nisantzi et al., 2014, 2015) and located in the city center of Limassol (see CUT-TEPAK site in the AERONET data base, TEPAK stands for the greek name TEchologiko PAnepistimio Kyprou). Unfortunately, the CUT-TEPAK AERONET photometer was not available from July to October 2015 for calibration reasons.

Details of the lidar data analysis regarding the retrieval of the particle linear depolarization ratio δ, backscatter coefficient β, extinction coefficient σ, and extinction-to-backscatter ratio (lidar ratio) S, and of the separation of dust backscatter coefficient β_{d} and non-dust backscatter coefficient β_{nd} are given by Tesche et al. (2009a, b), Mamouri et al. (2012, 2013), and Mamouri and Ansmann (2014), and Nisantzi et al. (2014, 2015).

The dust mass concentrations M_{d} is then obtained from the backscatter coefficients β_{d} by means of the equation,

$$M_{\mathrm{d}} = \rho_{\mathrm{d}} c_{\mathrm{v,d}} \beta_{\mathrm{d}} S_{\mathrm{d}} \,, \tag{1}$$

with the dust particle density ρ_{d}, assumed to be 2.6 $\mathrm{g/cm^{-3}}$ (Ansmann et al., 2012), the volume-to-extinction conversion factor $c_{\mathrm{v,d}} = v_{\mathrm{d}}/\sigma_{\mathrm{d}}$ with the dust volume concentration v_{d} , and the dust lidar ratio S_{d}.

By using a characteristic dust lidar ratio S_{d} (or even measured ones as during this dust storm), we convert the retrieved profiles of the backscatter coefficient β_{d} into respective profiles of dust extinction coefficient σ_{d}. We use S_{d}=40 sr for Middle East desert dust (Mamouri et al., 2013). Then, the dust extinction profile is converted into the particle volume and mass concentration profiles v_{d} and M_{d}, respectively, by using conversion factors from AERONET column observations during pure desert dust situations. Appropriate conversion factors were derived from extended studies during large dust field campaigns in Morocco, Cabo Verde, and Barbados (Mamouri and Ansmann, 2016). The average conversion factor $c_{\mathrm{v,d}}$ is $0.64 \pm 0.06 \times 10^{-12}$Mm.

The uncertainties in all the optical properties, conversion factors and estimated microphysical properties are discussed by Tesche et al. (2009a); Ansmann et al. (2012), and Mamouri and Ansmann (2014). Relative uncertainties in the dust backscatter and extinction coefficients and lidar ratios are about 10–20% at dense dust conditions. Considering in addition a relative uncertainty of 10% in the assumed dust density ρ_{d} and of about 10% in the conversion factor $c_{\mathrm{v,d}}$, we yield an overall relative uncertainty of 20–30% in the estimated dust mass concentrations.

2.2 MODIS observations of AOT

MODIS (Moderate Resolution Imaging Spectroradiometer, MODIS, http://lance-modis.eosdis.nasa.gov/) products are used to describe the dust load in the Cyprus region. For five sites we calculated the mean AOT at 550 nm wavelength and mean Ångström exponent (for the 510–670 nm spectral range) from the available set of AOT data within areas with 50 km radius around these cities. The maximum retrievable AOT is 5.0. On 8 September, this value was frequently exceeded. The uncertainty in the retrieved AOT is $0.05 \pm 0.15\times$ AOT (Levy et al., 2010, 2013).

2.3 PM_{10} observations of the Department of Labour Inspection of Cyprus

Non-validated hourly mean surface observations of PM_{10} concentrations are published by the Air Quality Department of Cyprus (Department of Labour Inspection, DLI, http://www.airquality.dli.mlsi.gov.cy/). We checked the uncertainty in the non-validated hourly values by comparing quality-assured 24-hour PM_{10} values (gravimetric method, European standard, kindly provided by DLI, personal communication, Chrysanthos Savvides) with respective 24-hour mean values calculated from the hourly mean non-validated data. We found deviations of ± 50 between the two daily means for the different sites of Larnaca, Limassol, and Pafos on 8 September 2015. The deviations reduced to about 20% later on (9–11 September).

2.4 Visibility observations of the Department of Meteorology of Cyprus

Another way to estimate the dust mass load at ground is based on observations of the so-called meteorological optical range (MOR) r_{vis} (better known as Koschmieder's visibility) (Koschmieder, 1924; Horvath and Noll, 1969; Horvath, 1971). We present visibility time series from three airports in Cyprus (Larnaca, Pafos, and Acrotiri, about 10 km southwest of the Limassol city center). The data are kindly provided by the Department of Meteorology, Cyprus (DoM, personal communication, Filippos Tymvios). The visibility values are estimated by human observers which are carefully trained after the guidelines of the World Meteorological Organization. The uncertainty of the MOR estimation is of the order of 20–30% for $r_{\mathrm{vis}} >$1000 m up to 20 km. For lower MOR, the uncertainty may be considerably higher.

The visibility r_{vis} is linked to the particle extinction coefficient σ for 500–550 nm (in the visible wavelength spectrum) by the relationship (e.g., Horvath and Noll, 1969; Horvath, 1971)

$$\sigma = 3.0/r_{\mathrm{vis}} \times 10^6 \tag{2}$$

with r_{vis} in m and σ in Mm^{-1}. The AOT of 3.0 describes the attenuation of light along the horizontal distance with length r_{vis}. Eq. (2) is based on the original Koschmieder formula. Koschmieder (1924) used an AOT of 3.9 which causes an apparent contrast of the object against the bright background of 0.02. The AOT of 3.0 is related to the intuitive concept of visibility through the contrast threshold taken as 0.05.

Under clear-air conditions, the particle extinction coefficient at 500–550 nm is about 50–150 Mm^{-1}. MOR is then in the range of 20–50 km. In the Eastern Mediterranean around Cyprus, we may add a marine aerosol contribution to particle extinction by about 50–100 Mm^{-1} so that the visibility is usually between 10–30 km in the polluted marine environment. During the strong dust outbreak in September 2015, however, the visibility dropped to values of the order of 300-1000 m, which corresponds to dust extinction coefficients of the order of 3000-10000 Mm^{-1}. At these conditions, contribution of marine and anthropogenic particles to the total particle extinction coefficient of the order of a few percent can be neglected.

In order to compare the visibility observations and in situ PM_{10} mass concentrations, we convert the derived particle extinction coefficients σ_d into dust mass concentrations M_d by using the relationship (compare Eq. (1))

$$M_\mathrm{d} = \rho_\mathrm{d} c_\mathrm{v,d} \sigma_\mathrm{d} \tag{3}$$

with the volume-to-extinction dust conversion factor $c_\mathrm{v,d}$ of $0.64 \pm 0.06 \times 10^{-12}$Mm and the dust particle density ρ_d of 2.6 $\mathrm{g/cm}^{-3}$, as introduced in Sect. 2.1. The uncertainty mainly depends on the uncertainty in the visibility estimation.

3 Results

3.1 Dust transport features: Horizontal and vertical dust distribution

Fig. 1 provides an overview about the enormous dust storm in the beginning of September 2015 as seen by MODIS. Optically dense dust plumes were advected from the east and reached Cyprus on 7 September 2015. Parts of the dust plumes were so dense that the dark surface of the Mediterranean Sea and eastern and southern parts of the island of Cyprus were no longer visible from space. The highest dust load was observed over Cyprus on 8 September 2015. On this day, the 550 nm AOT clearly exceeded 5 as will be discussed in detail in the next subsection. Unfortunatly, lidar observations were not possible on 8 September. The dust amount slowly decreased and showed a second, much weaker maximum on 10–11 September. The Troodos mountains (dark area in southwestern Cyprus) with top heights up to 2000 m were always visible during the dust storm (even on 8 September, AOT>5). This indicates that the thickest dust layers crossed Cyprus at heights below 1500 m height. This conclusion is supported by the lidar observations.

To provide a coarse idea information about the dust source regions and insight into the main airflow during this dust event, Fig. 2 shows six-day backward trajectories for 8 September 2015 (9 UTC) for arrival heights in the lower dust layer (reaching to about 1.5 km height according to the Limassol lidar observations on 7 and 9 September, also clearly visible in the Nicosia radiosonde profiles of temperature and relative humidity (RH)on 8 September, 6 and 12 UTC launches, as will be discussed below) and in the upper dust layer (from 1.5–3.8 km as indicated by the Nicosia temperature and RH profiles) over the Eastern Mediterranean at 34.7°N and 35°E), about 160 km east of Limassol. The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory, http://www.arl.noaa.gov/HYSPLIT.php) model was used for this purpose (Stein et al., 2015). Dust from Middle East deserts were transported to the northwest towards northern Iraq and northeastern Syria, and then to the west towards the Mediterranean Sea.

Figure 3 presents the Limassol lidar observations of the vertical dust layering observed from 7-11 September 2015. As mentioned, dust advection occurred in two pronounced, separated dust layers (the lower one up to 1.5–1.7 km, the upper one up to 3.5-4.2 km height) on 7-9 September. A first thick dust layer crossed Cyprus in the evening of 7 September between 2 and 3.7 km height. The detected two-layer structure prevailed on 8 September (no lidar observations to avoid any potential damage of lidar optics and detection units). This is corroborated by the profiles of temperature and RH measured with radiosondes launched at Nicosia about 60 km northeast of Limassol at 6 and 12 UTC. The peak dust front reached Limassol between 8–9 UTC. The vertical gradients of temperature and RH were different in the two layers. Furthermore, the 12 UTC RH profile increased from values of 10–15% at the surface to about 30% at the top of the lower layer in 1.5 km height and indicated well-mixed dust conditions. Similarly, the potential temperature was almost height independent and thus also indicated favorable conditions for vertical mixing. In the upper layer from 1.5–3.8 km height, slightly stable conditions were observed.

Figure 4 depicts the two-layer dust structures in terms of dust mass concentration derived from the lidar observations in the evening of 7 September. The values exceeded already 2000 μg/m^3 below 1500 m height and 600 μg/m^3 around 3 km height on 7 September 2015. The two–layer structure of the dust plume is well reflected in the meteorological data measured with the Nicosia radiosonde on 8 September, 6 UTC, just before arrival of the main dust front. As mentioned above, the changes in RH and potential temperature with height indicated different air masses and thus different dust source regions above and below about 1500 m height. The meteorological data also indicate that the dust layer was still lofted (base height at around 700 m above ground) in the morning of 8 September, at 6 UTC.

The same two-layer structure was then observed again with lidar a day later on 9 September 2015 (see Figure 3), again in consistency with the temperature and humidity profiles of the Nicosia radiosonde. In the evening of 10 September, another elevated optically dense dust layer crossed the EARLINET lidar station. Finally, on 11 September, a more homogeneous and temporally constant layering was found. The main layer was now below 2000 m. Traces of dust were however detected up to 3000–4000 m height. On 12 September (not shown), a strong decrease in the AOT values indicated the end of the dust episode.

In Fig. 5, four photographs taken on 8 September 2015 at local noon (during the passage of the main, rather dense dust front) from the roof of a high building (AERONET station) at Limassol to the south and north are presented. The left photographs show the situation during the phase with the heaviest dust load (8 September, around local noon). These pictures are in strong contrast to the photographs taken one day later, when the dust concentration was still high but the horizontal visibility increased already to values of around 8–10 km. By careful inspection of the pictures from 8 September (searching for different pronounced buildings and towers) we estimated the horizontal visibility to be 500–600 m. The visibility measurements performed at three airports in Cyprus are discussed in the next subsection. A visibility of 500 m points to dust extinction coefficients of about 6000 Mm^{-1} according to Eq. (2). If this extremely high extinction coefficient occurred at all heights throughout the lower dust layer up to 1.5 km height, as suggested by the 12 UTC radiosonde RH profile, we end up with AOTs of close to 9. Even if we assume a lower average extinction value of 4000 Mm^{-1}, the AOT would be close to 6. Such huge dust optical depths indicate column dust loads of 10–15 g/m^2. In the upper layer, the AOT was significantly lower with values around 0.5 or less as the lidar observations on 7 and 9–11 September indicate. This is consistent with the fact that the higher parts of the Troodos mountains remained always visible, even on 8 September in Fig. 1.

Figure 4 also shows height profiles of the dust outbreaks simulated with the RAMS-ICLAMS model (Regional Atmospheric Modeling System / Integrated Community Limited Area Modeling System) (Cotton et al., 2003; Solomos et al., 2011). Details to this simulations are given in the follow-up paper (Solomos et al., 2016, in preparation). Dust profiles for arrival times in the evening of 7 September and local noon of 8 September 2015 are shown. The regional model (simulation with 20 km horizontal resolution) clearly underestimates the dust load. As explained in detail by Solomos et al. (paper in preparation) the event seems to be the result of two meteorological processes. A thermal low formed over Syria on 6 September 2015 associated with strong cloud convection and provided favorable conditions for the generation of a haboob along the borders between Iraq-Iran-Turkey-Syria on 7 September 2015. Atmospheric density currents evolved and propagated towards the Mediterranean and pushed the pre-existing elevated dust layers towards the Mediterranean Sea. The main reasons that most dust prediction models (including RAMS in regional modeling configuration with too low horizontal resolution to resolve cloud convection processes) did not capture this episode are possibly related to the lack of sufficient physics package to describe the feedback of clouds on dust mobilization and the lack of sufficient (cloud resolving) model resolution. A detailed discussion is given in the follow-up study (Solomos et al., paper in preparation).

3.2 Dust optical properties and mass concentrations: surface and profile observations

Figure 6a shows time series of AOT retrieved from daily MODIS observations for four coastal sites from Risocarpaso at the most eastern tip of Cyprus to Pafos, which is approximately 250 km southwest of Risocarpaso. In addition, the AOT time series for the capital city Nicosia is shown. The mean AOT values for areas with radius of 50 km around these cities are presented. Only values that passed a quality check (QAC) are included in the averaging. These are level-2 single pixel AOT(550 nm) measurements with a QAC flag of 3 and a QAC flag greater than 0 were used over land and over ocean, respectively. The maximum retrievable AOT is 5.0. Many of the individual validated (pixel) AOT values were set to 5.0 (although the true value was larger). For Fig 6, we used all validated data points in the averaging. Therefore, the area mean values for 8 September (Julian day 251) have to be interpreted with caution. Furthermore, as outlined in the foregoing section, the uncertainty in the retrievable AOT values is about $0.05 \pm 0.15 \times$AOT.

One can see that the AOT at Limassol was around and above 1.0 for four days (8-11 September). We speculate that the maximum AOT was in the range of 6-9 on 8 September 2015, as discussed above. Our lidar observations on 7 and 9-10 September indicate that the AOT contribution of the second layer above 1.5 km height was always of the order of 0.5.

According to MODIS, the AOT ranged from 0.85–1.7 on 9 September 2015, 1.2–2.1 on 10 September, and 1.1–1.4 on 11 September over southern Cyprus (Larnaca, Limassol). The AOT was considerably lower at Pafos on 9–10 September, 70 km west of Limassol, with values of 0.4 and 0.3–0.7, respectively. In comparison, our lidar observations (taken about 6–11 hours after the daily MODIS observations) indicate AOTs of 0.5-0.6 on 9 September (MODIS, Limassol, 0.85, Pafos 0.4), 0.7–0.75 on 10 September (MODIS, Limassol 1.2, Pafos, 0.3–0.7), and around 0.85 on 11 September (MODIS, Limassol, 1.1, Pafos, 0.8). On 12 September 2015, all three stations showed significantly reduced dust loads with AOT values from 0.3–0.8 derived from the MODIS observations. In this context it should be mentioned that the relative humidity was always $<30\%$, $<40\%$, $<50\%$ within the lowermost one kilometer, up the top of the lower dust layer, and up to the top of the upper dust layer, respectively, on 7–11 September, so that effects of aerosol particle growth by water uptake on the observed AOT values can be neglected. The impact of anthropogenic particles and marine particle may have been of the order of 0.05–0.15 and 0.03–0.05 on the total AOT at 500 nm during the dust period.

Figure 6b shows that the Ångström exponent (AE), which describes the wavelength dependence of AOT (for the visible wavelength range from 510–670 nm), dropped from typical values of 1.0–1.5 for mixtures of anthropogenic aerosol and marine particles (and some local dust) to values around 0.3 during the dust period (ignoring the low AE values on 8 September which are mostly based on biased AOT values).

Figure 6c presents the surface observations of PM_{10} concentrations from 6-14 September 2015. Hourly mean values for five sites across Cyprus are shown. The uncertainty in this values is of the order of 50%. The maximum hourly mean dust mass concentration at Limassol was close to 8000 μg/m^3 on 8 September. The quality-assured daily mean values were 2900 μg/m^3 (Larnaca), 1500 μg/m^3 (Limassol), and 500 μg/m^3 (Pafos) on 8 September, 2015.

The PM_{10} observations may have underestimated the total-suspended-particle (TSP) mass concentration. Kandler et al. (2009) showed that the TSP mass concentration can be an order or even two orders of magnitude larger than the respective PM_{10} value during haze periods and density current-induced dust fronts. TSP mass concentrations of up 300000 μg/m^3 were observed in southeastern Morocco, close to the Sahara, and simultaneously, the PM_{10} values was of the order of 3000 μg/m^3 only. Particles with diameters $>$10 μm often accounted for more than 90% of the total airborne aerosol mass in southeastern Morocco. At Cabo Verde, after long range transport of dust over 1000–3000 km, the TSP-to-PM_{10} particle mass concentration ratio was found to be mostly between 1.2–1.5 Kandler et al. (2011).

To check to what extend the PM_{10} dust observations underestimated the TSP mass concentration during these extreme dust conditions of 8 September 2015, we analyzed visibility observations at three airports in southern Cyprus. According to Eq. (2) in Sect. 2.4, the visibility is directly related to the particle extinction coefficient, which in turn is highly correlated with the particle volume and mass concentration. The relative uncertainty in the derived mass concentration is estimated to be about 30-40%, provided the visibility is available with an uncertainty of 20-30%.

Figure 7 shows time series of visibility and corresponding extinction coefficient. All three stations show visibilities in the range from 200-750 m from 5:00 to 20:00 (Larnaca), 6:00–14:00 (Limassol), and 10:00–14:00 (Pafos). The lowest visibilities of 200–300 m values in the Limassol area were observed at Acrotiri airport (about 10 km southwest of the Limassol lidar station) from 8–9 UTC, when the photographs in Figure 5 were taken. The corresponding particle extinction and mass concentration values for Acrotiri are 9000–15000 Mm^{-1} and 15000–25000μg/m^3, respectively. As mentioned in Sect. 2, marine and anthropogenic haze may have contribute to the total aerosol extinction coefficient by 50–100 Mm^{-1} each so that their contribution to observed extinction values exceeding 2000 or 3000 Mm^{-1} can be ignored in the following discussion and retrievals.

The visibility of 500 m is related to peak particle extinction coefficient of 6000 Mm^{-1} and correspondingly to a peak TSP mass concentration of 10000 μg/m^3. This peak TSP value is about a factor of 1.25-1.3 higher than the in situ measured maximum hourly mean PM_{10} value of around 7600 μg/m^3. This can be regarded as an excellent agreement when taking the study of Kandler et al. (2011) on the relationship between TSP mass versus PM_{10} into consideration.

However, if we compare the quality-assured daily mean in-situ measured PM_{10} values for Larnaca (2900 μg/m^3), Limassol (1500 μg/m^3), and Pafos (500 μg/m^3) on 8 September 2015, with the respective daily mean TSP mass concentrations (calculated from MOR values measured every hour), we find visibility-related daily mean TSP mass concentrations of 3600 μg/m^3

(Laranca), 2075 μg/m^3 (Acritori, Limassol), and 1600 μg/m^3 (Pafos), which are a factor of 2.5 (Larnaca), 2.8 (Limassol), and 6.4 (Pafos) higher than the in-situ measured PM_{10} daily means. These very high (and to our opinion unrealistic) factors of 2.5–6.4 may be caused by a wrong volume-to-extinction conversion factor $c_{\rm v,d} = v_{\rm d}/\sigma_{\rm d}$ (a factor of 2 too high) in Eq. (3), or by a wrong visibility estimations (roughly a factor of 2 too high) at these unusual very dust conditions. The volume-to-extinction conversion factor is 0.64×10^{-12}Mm (as discussed in Sect. 2.1). A value around 0.32×10^{-12}Mm points to conditions with dominating fine-mode dust (Mamouri and Ansmann, 2016). At strong dust outbreak conditions we expect the opposite, namely that coarse-mode dust particles dominate the measured optical effects so that the volumne-to-extinction conversion factor higher than 0.64×10^{-12}Mm.

The next days showed steadily decreasing near-surface dust mass concentrations. The daily mean PM_{10} mass concentration decreased from 2900 μg/m^3 (8 September) to 1000, 500, and 200 μg/m^3 on the following day (9–11 September) at Larnaca, and from 1500 μg/m^3 (8 September) to 500, 200, and 200 μg/m^3 at Limassol on 9–11 September. This steady decrease of the near-surface dust mass concentration was not observed for the total column (see discussion of MODIS and lidar-derived AOTs above) which remained almost constant from 9–11 September.

The highlight of the observations are our lidar observations of the vertical layering of the dust particles. Such profile observations are indispensable in the verification of modeling results and the reliability of model-based dust outbreak studies as a whole. Figure 3 provides an overview of the main dust layering features and indicated a two-layer structure of the advected dust plumes which pointed to two different air mass transport regimes and thus two dust source regions.

In Fig. 8, profiles of particle backscatter and extinction coefficients at 532 nm, the corresponding extinction-to-backscatter ratio (lidar ratio), and the particle linear depolarization ratio at 532 nm for each of the four evenings on 7 and 9–11 September are given. 1-hour to 3-hour mean profiles provide an overview of the main features of the dust optical properties. The backscatter coefficients are obtained with high vertical resolution (signal smoothing window length of 195 m) and show best the layer structures. The profiles of the particle backscatter coefficient and the particle linear depolarization ratio are trustworthy down to 100 m above ground as the comparison with the surface in situ observations (PM_{10} measurements, visbility/extinction observations) corroborate which will be discussed below. The extinction coefficients and corresponding lidar ratios are calculated from smoothed Raman signal profiles (375m smoothing length).

The particle extinction coefficients reached values of 1300 Mm^{-1} in the lower layer and were around 350 Mm^{-1} in the second layer on 7 September. Another pronounced dust front caused extinction coefficients up to 550 Mm^{-1} in an elevated layer between 1000 and 2500 m height on 10 September 2015. The lidar ratios at 532 nm were 35-42 sr in the dust layers on 7 and 10 September, 45-60 sr on 9 September, and 50-60 sr on 11 September. Values of 35–45 sr are typical for desert dust from Middle East dust sources (Mamouri et al., 2013; Nisantzi et al., 2015). Larger lidar ratios on 9 and 11 September indicate a mixture of dust and anthropogenic haze. As mentioned above, hygroscopic particle growth effects on the oberved optical properties can be neglected.

The particle linear depolarization ratio assumed typical dust values of 0.25-0.32 (7 and 10 September) in the dense dust layers. These values clearly indicate the dominance of mineral dust in these layers. The decrease towards values of 0.20-0.25 on 9 and 11 September reflects the increasing impact of anthropogenic haze on the optical properties of the advected air masses.

The linear depolarization ratio dropped to values clearly below 0.2 in the lowermost 300–500 m thick marine boundary layer over Limassol and was around 0.1–0.15 at 100 m above ground. Such low depolarization ratios indicate that anthropogenic pollution contributed to more than 50% to the overall total particle backscattering and extinction coefficients and to 30–50% to the particle mass concentration in the city. This fact has to be kept in mind when comparing PM_{10} mass concentrations with the mass concentrations derived from the lidar profiles at heights below about 300–500 m.

The backscatter and extinction profiles and the lidar ratio information allow us to estimate the AOT in the lower dust layer (partly from the backscatter coefficients) and to termine the AOT at 532 nm in the upper dust layer, from the extinction profile. We estimated the extinction values in the vertical range without extinction measurements (in the lowermost about 800 m) by multiplying the backscatter coefficients with a lidar ratio of 50 sr which is higher than a pure-dust lidar ratio and takes the influence of anthropogenic pollution (lidar ratios of 60-80 sr) into account. On 7 September, the 532 nm AOT for the lower layer (0–1.7 km height) was 1.2, and 0.5 for the upper layer from 1.7–3.5 km. On 9 September, the 532 nm AOT decreased strongly from the record-breaking values $>$5.0 on 8 September to values around 0.5 with an AOT around 0.35 for the lowermost 1.2 km height region and 0.2 for the upper dust layer from 1.2–3.0 km height. In contrast to the evening lidar observations, the morning MODIS data revealed still an AOT of 0.8-1.0 on 9 September. Another dense dust outbreak plume then reached Cyprus on 10 September. The daytime AOT (MODIS) for Limassol showed a slight increase to 1.0–1.2, the lidar observed an overall AOT of 0.7–0.8 (as three hour average) in the nighttime of 10 September 2015. The lower dust layer (up to 1 km height) contributed about 0.2–0.3 and the upper layer (1–3 km) around 0.5 to the total AOT. A more vertically homogeneous dust extinction backscatter and extinction profiles were observed on 11 September with an AOT of around 0.6 for the lower part (0–1.8 km height) of the dust layer and an AOT of about 0.25 for the upper part from 1.8-4.2 km height. MODIS AOT values on 11 September were still around 1.0 (for all stations Larnaca, Limassol, Pafos). Thus a good agreement between MODIS and lidar observations was found for this final dust day.

We also studied to what extent the lidar backscatter coefficients and the estimated extinction values close to the ground are reliable. Visibility observations yield values for the meteorological optical range of around 8–10 km in the evening of 9 September, which corresponds to particle extinction coefficients of 300–375 Mm^{-1}. The lidar measurements indicate backscatter coefficients of 6 Mm^{-1} sr^{-1} close to the surface on 9 September, and thus extinction coefficients of 275 Mm^{-1} (by multiplying the backscatter coefficient with a lidar ratio of 45 sr, representing dust-dominated conditions) to 330 Mm^{-1} (for a lidar ratio of 55 sr, representing urban-haze-dominating conditions). The good agreement indicates that urban haze controls the surface-near aerosol extinction coefficient which is corroborated by the low particle linear depolarization ratio of 0.08-0.15 at heights $<$500 m.

An overview of the vertical dust mass distribution, observed in the evenings of 7, 9, 10, and 11 September 2015, is given in Fig. 9. In Eq. (1), we used the dust lidar ratio of 40 sr. After the first very dense dust plumes on 7-8 September, another dense dust plume crossed Limassol in the evening of 10 September and the dust mass concentrations was again high with values close to 800 μg/m^3 in the center of the elevated layer from 1000-2500 m height. The two-layer structure vanished on 11 September. Only one layer extending from the surface up to 4.2 km height was observed. In terms of column dust mass concentrations we obtained values of 1.9 g/m^2 (for 7 September in Fig. 9), 0.35 g/m^2 (9 September), 0.95 g/m^2 (10 September), and 0.6 g/m^2 (11 September). AOTs of 6–9 as estimated for the peak dust front on 8 September indicate peak column dust loads of 10–15 g/m^2.

Regarding the quality of the lidar-derived TSP mass concentrations close to the ground, we compared the lidar data with respective PM_{10} observations (mean values for the lidar measurement periods in Fig. 9). The Limassol evening PM_{10} values (considering dust and aerosol pollution) were 55 $\mu g/m^3$ (7 September), 120 $\mu g/m^3$ (9 September), 125 $\mu g/m^3$ (10 September), and 165 $\mu g/m^3$ (11 September). The respective lidar-derived total aerosol mass concentrations were 65 $\mu g/m^3$ (7 September), 180 $\mu g/m^3$ (9 September), 125 $\mu g/m^3$ (10 September), and 290 $\mu g/m^3$ (11 September). The uncertainties are roughly 30% for the lidar mass values and 50% for hourly-mean PM_{10} values. Again, good agreement is obtained keeping the uncertainties in the derived values into account. Inhomogeneous downward mixing of dust and horizontal inhomogeneities in the dust and urban pollution distributions may have also contributed to the differences. Note, that Fig. 9 only shows the dust-related mass concentrations. The contribution of urban and marine aerosol to the TSP mass concentration was of the order of 20–30 $\mu g/m^3$ (7 and 10 September) and 40–50 $\mu g/m^3$ (9 and 11 September 2015).

4 Conclusions

A record-breaking dust storm over the Eastern Mediterranean in September 2015 has been documented and discussed based on satellite, lidar, and in situ aerosol observations in the Cyprus area. We were able to provide a consistent picture of this dust event in terms of a variety optical and microphysical, and dust layering properties obtained by means of very different in situ and remote sensing observational techniques and retrieval approaches. The highlight of the study were the vertically resolved lidar observations. The presented documentation of an extreme dust storm based on state-of-the-art lidar, satellite and in situ observations is a valuable contribution to the literature dealing with long-range transport of dust, forecasting of dust outbreaks, and the research on the relationship between meteorological conditions and dust emission strength.

Such unique events may take place once in a decade or even less frequently and are thus obviously linked to unique meteorological constellations. The documentation of extremely seldom dust storms with vertical, horizontal and temporal resolution (in this article) in combination with advanced atmospheric modeling covering cloud evolution, development of thunderstorm, density currents, dust mobilization and dust transport (in the follow-up article) will certainly lead to an improved understanding of the evolution of dust storms at extreme meteorological conditions. The modeling studies will further reveal what kind of modeling infrastructure is required to resolve even small-scale hot spots of dust mobilization phenomena in order to improved dust forecasting in general.

Another concluding remark deals with the need of a dust lidar network around the main desert areas, e.g. in the Europe-Africa-Asia region from the Sahara, over the Middle East deserts to the desert regions in central, southern and eastern Asia. Continuously operated lidars would be an ideal supplement to dust forecast dust model efforts with the potential goal to assimilate the lidar products in to the forecast models. As demonstrated in this article, modern polarization lidars allow us to separate dust and non dust optical properties and to quantify the dust-related particle extinction coefficient and mass concentration in the vertical profile profile with an uncertainty of 20-30%.

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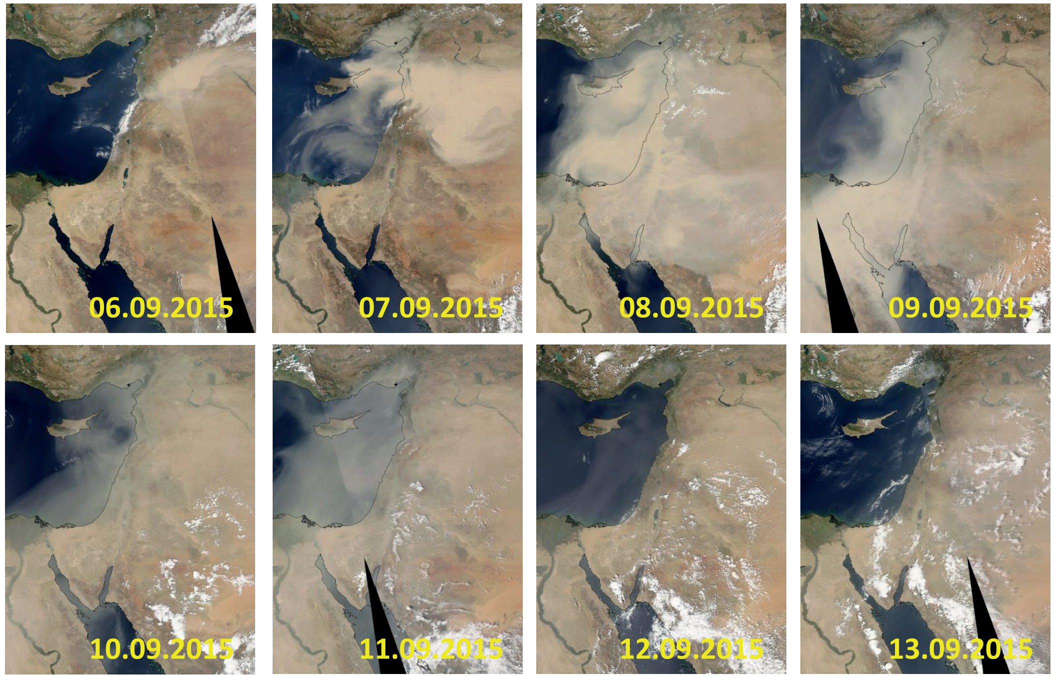

Figure 1. Dust outbreak towards Cyprus in September 2015 as seen from space (AQUA-MODIS, 10:30-11:30 UTC overpasses, 13:30–14:30 EEST, Eastern European Summer Time, http://lance-modis.eosdis.nasa.gov/).

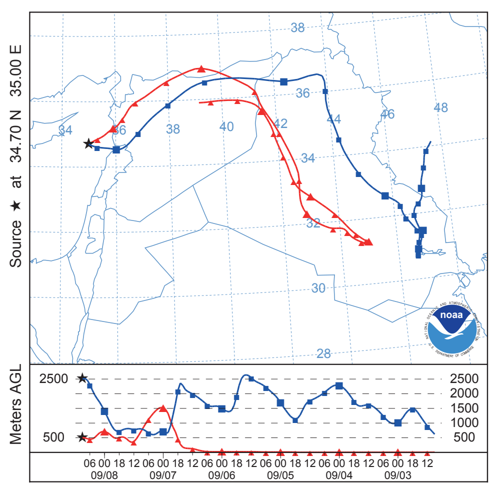

Figure 2. Six–day HYSPLIT backward trajectories (http://www.arl.noaa.gov/HYSPLIT.php) arriving in the Cyprus region at 35°E (about 160 km east of the Limassol lidar station) at 500 m (red, lower dust layer) and 2500 m height (blue, upper dust layer) on 8 September 2015, 09:00 UTC (12:00 EEST)

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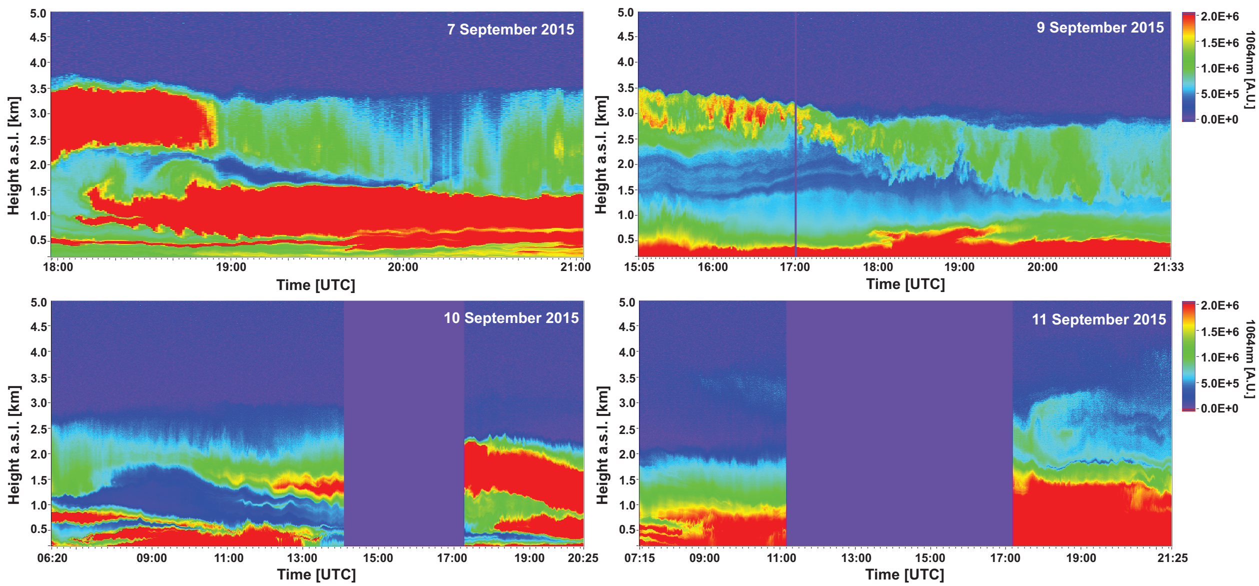

Figure 3. Desert dust layers observed with lidar over the EARLINET station of Limassol, Cyprus, on 7, 9, 10, and 11 September 2015. Range–corrected 1064 nm backscatter signals (in arbitrary units, A. U.) are shown. Red colors indicate dense dust plumes. On 7-10 September, a two-layer structure was observed with dust layers below about 1-1.7 km height and another layer reaching to 2.5-3.7 km height. Local time (EEST) is time in UTC plus 3 hours.

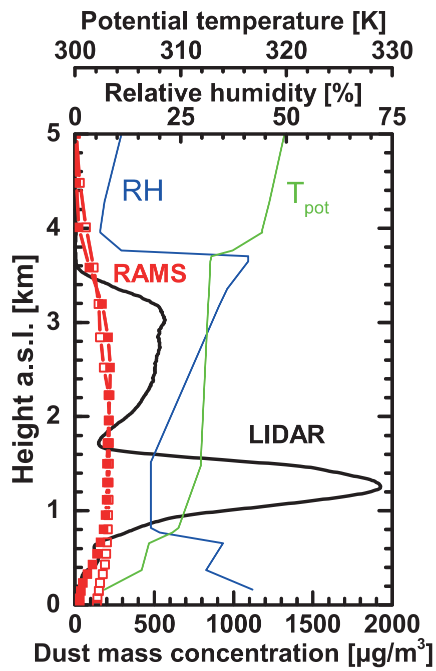

Figure 4. Mean dust mass concentration observed with lidar (thick solid black line) at Limassol on 7 September, 18:00–21:00 UTC, and dust profiles simulated with RAMS (normal run with 20 km horizontal resolution) for Limassol, on 7 September, 18:00 UTC (closed red squares), and 8 September, 9:00 UTC (open squares). Radiosonde observation (launched at the radiosonde station at Athalassa near Nicosia on 8 September 6:00 UTC) of height profiles of potential temperature (T_{pot}, thin green curve) and relative humidity (RH, thin blue curve) are in good agreement with the two-layer dust structures observed about 12 hours earlier. The lofted dust layer from 1.7-3.6 km height was well mixed.

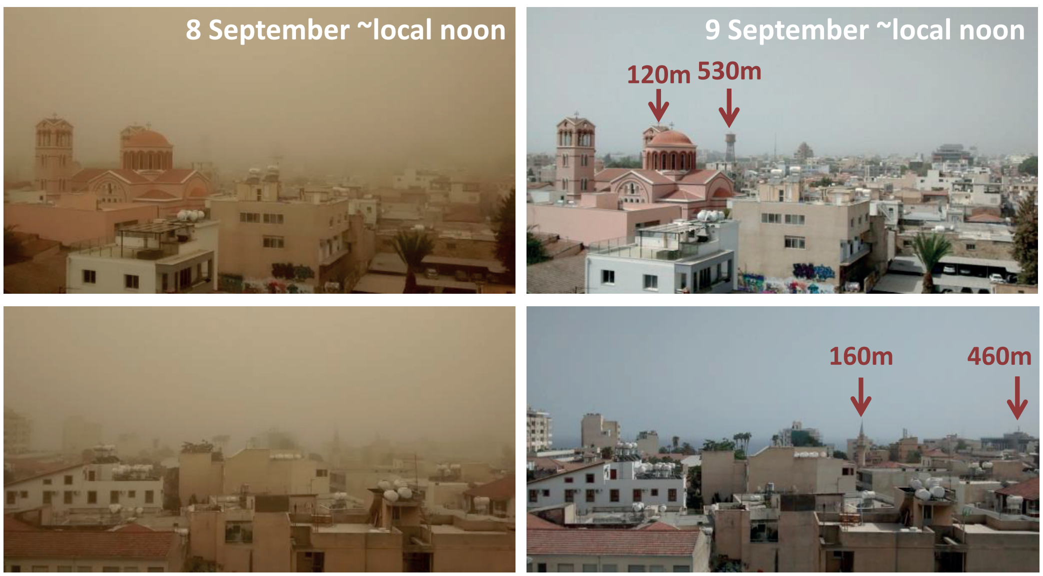

Figure 5. Photographs taken at the roof of a high building (CUT-TEPAK AERONET site) in the city center of Limassol to the north (top) and south (bottom) on 8 September 2015, 8:20-8:30 UTC (left) and on 9 September 2015 (right), again around local noon. The meteorological optical range (or horizontal visibility) was about 500 m on 8 September and higher than 20 km on 9 September 2015. Distances to several towers from the AERONET station are indicated.

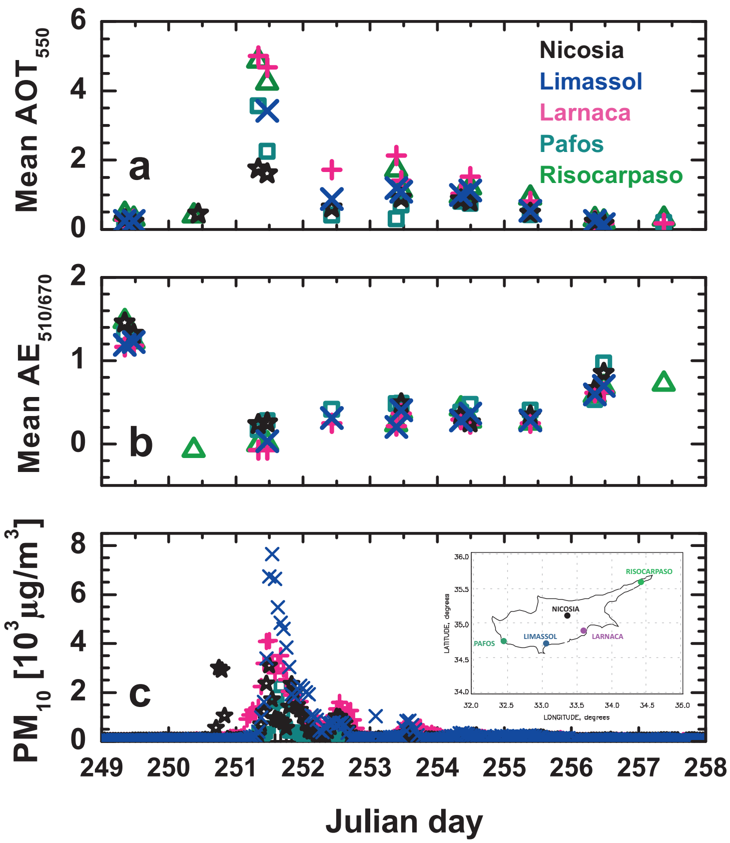

Figure 6. (a) MODIS-derived mean 550 nm aerosol optical thickness (AOT) for five sites in Cyprus for the period from 6-14 September 2015 (Nicosia, stars, Limassol, diagonal crosses, Larnaca, crosses, Pafos, squares, Risocarpaso, triangles, AQUA-MODIS, 10:30-11:30 UTC, and TERRA-MODIS, 8:00–9:00 UTC overpasses), (b) MODIS-derived Ångström exponent (for the 510–670 wavelength range), and (c) hourly mean PM_{10} particle mass concentrations measured at four stations in Cyprus (Nicosia, Limassol, Pafos, Larnaca). The AOTs are determined from all MODIS values within areas with 50 km radius around a given site. MODIS data are available at https://ladsweb.nascom.nasa.gov/data/search.html. The highest retrievable AOT is 5.0. An area-mean values >3.5 are probably biased (underestimation of the true mean AOT, see text). The in situ aerosol observations were performed by the Air Quality Department (Department of Labour Inspection of Cyprus at Limassol) and are available at http://www.airquality.dli.mlsi.gov.cy/. The peak PM_{10} concentration of 7600 μg/m^3 was observed around 9 UTC on 8 September 2015 (Julian day 251)

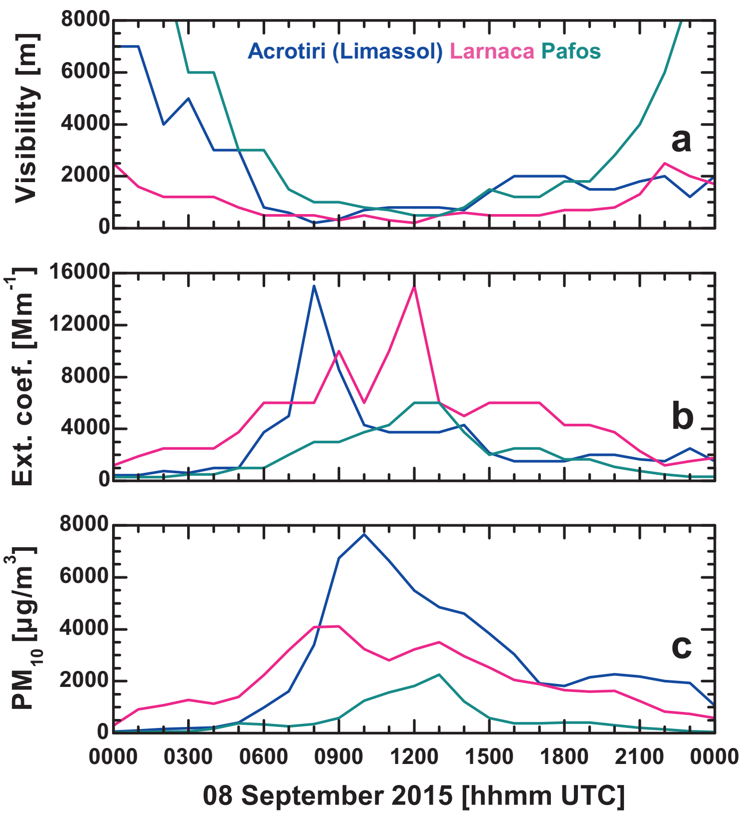

Figure 7. Visibility measured at three airports in southern Cyprus (see map in Fig. 6c) on 8 September 2015, (b) corresponding dust extinction coefficient (by using Eq (2)), and (c) PM_{10} concentrations (same as shown in Fig. 6c). Relative uncertainties in all parameters of of the order of 50%. Dust extinction coefficients of 4000–8000 Mm^{-1} indicate dust mass concentrations of 6600–13300 μg/m^3.

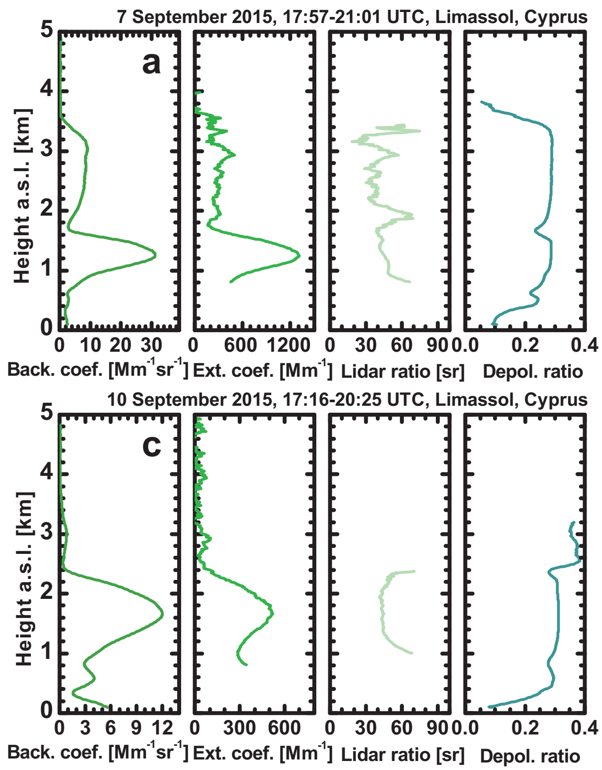

Figure 8. Mean vertical profiles of the 532 nm particle backscatter coefficient, extinction coefficient, lidar ratio, and particle linear depolarization ratio for the observational periods given on top of the panels on 7–11 September 2015. The Raman lidar method is applied. Retrieval uncertainties are of the order of 10% (backscatter coefficient, depolarization ratio), 25% (extinction coefficient), and 30% (lidar ratio).

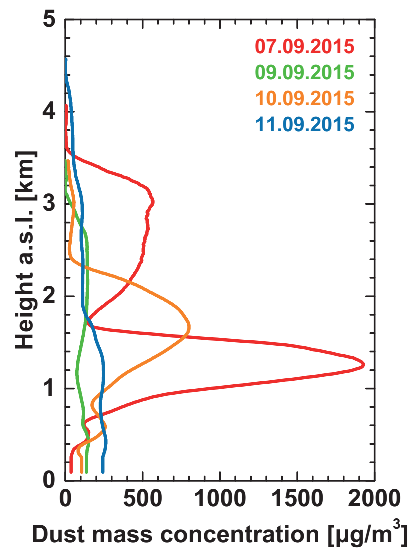

Figure 9. Lidar-derived mean dust mass concentrations for the evening periods (see Fig. 8) of 7 September (18:00–21:00 UTC), 9 September (19:00–21:28 UTC), 10 September (17:16–20:25 UTC), and 11 September (17:11–21:25 UTC). The overall uncertainty in the retrieval of the dust mass concentration is 25%.