Dear Editor, Dear Reviewers!

Thank you again for taking the time for careful reading. We included the majority of your suggestions in the revised manuscript. They improved the paper again…

The main points of improvement are:

- We analyzed all MODIS overflights (Limassol overpasses) from 2001 to 2015 (about 5000 overpasses) and carefully created a terra-MODIS (2001-2002)-aqua-MODIS (2003-2015) AOT time series for Limassol (considering one observation per day, all in all 2018 daily observations). Then we checked this MODIS AOT data set for strong and extreme dust events. And as we already speculated, the extreme high 8-September 2015 AOT was by far the highest within this 15 year period. This is now shown in the introduction. We present a new figure (Fig.1) based on this 15-year AOT data set. We think that an extraordinary event (this September 2015 dust event) needs an extraordinary introduction with this figure as a highlight.

- We also performed a careful MODIS-AERONET AOT comparison by using AERONET data from Agia Marina/Nicosia (for moderate AOTS of 0.5-1.0) and the Weizmann Institute (Israel, AOT>2.5) for the September 2015 dust period. In addition, we used Limassol AERONET data (AOT>3.0, April 2013). We found a clear systematic overestimation by MODIS of the order of 0.5-1.5 for high AOTs (>2.5). This is discussed in the methodology section 2.2.

- We tried again to be less speculative regarding the peak AOT on 8 September, we simplified the discussion (following the suggestion of the reviewer who asked for major revisions) by assuming a well-mixed dust layer up to 800 m or 1500 m. With an extinction coefficient of 6 km-1 we end up with AOTs of 4.8 to 9. These value corroborate the MODIS data, which suggest AOT>5.0. We feel that such a speculative discussion is tolerable (not to say necessary) in a case of such an extraordinarily strong, unique dust storm.

- We integrated new literature mentioned by two reviewers.

Step-by step answers (our answers in bold)

Editor's comment:

I also have a comment to add: You refer to the occurrence rate of such heavy dust events at various occasions in the text. Where does this estimate come from? I think you should either back up this claim with references/measurements or omit it as it is rather speculative. Are the time series of ground-based PM10 observations at Cyprus (or in the region) long enough to assess the occurrence rate of such extreme dust events?

As mentioned above, we analyzed the MODIS data from 2001-2015, and calculated area mean AOTs around Limassol (all data within 25 km radius around city center), we then calculated the mean value and the threshold value for a strong dust case (defined by an AOT>0.70 up to 1.15, mean plus 2 times standard deviation) and an extreme case (defined by an AOT of 1.15, mean plus 4 times standard deviation). According to the new Figure 1, we found 12 extreme dust storms with AOT>1.15 in these 15 years, most AOTs of these extreme events were below 2.0, only two (1 April

2013, AOT of 4.2, and 8 September 2015, AOT of 4.9) exceeded 4.0. This is now emphasized in the Introduction section, in the first paragraph, based on Figure 1.

PM10 time series are at all not useful, because Saharan dust storms are often lofted, whereas the Middle East storms often cover the entire lower troposphere from the surface up to 4 km height. During the Saharan dust storm on 1 April 2013 with AOT of around 4.0 (at noon according to AERONET), the maximum dust mass concentration was 1300 µg/m3, on 8 September 2015, it was 7600 µg/m3.

…………………………………………………………………………………….

Reviewer #1 (minor revisions):

I found some parts difficult to follow. There were results mentioned in the methodology part and vice versa. It would be beneficial if you could work on the structure of the manuscript.

Guided by your detailed hints (below), we tried to better separate methodological points (went into section 2) and results (went into section 3)

page 2, line 35 Consider including Preißler et al. (2011).

Done (Introduction), now cited. We carefully checked the literature months ago, but obviously overlooked this very relevant paper. Sorry!

page 4, line 5 What output does MODIS provide for AOT>5? Are those data points set to 5? Please include this information here (it is mentioned in the results section).

We explain it better now (section 2 as well as in the result section). Yes, there are many data points just set to 5.0 in the MODIS data base (indicating that the true AOT was larger than 5.0). However, we used all available data in the averaging, so also these 5.0 values….. Consequently, the true AOT is underestimated in this way. Even if we would exclude all 5.0 values, the AOT would be biased (strong underestimation of the true area mean AOT).

page 4, line 5 move "On 8 September, this value was frequently exceeded." to results section

Improved

page 4, line 12-13 move "We found ... September)." to results section

Improved

page 5, line 1-3 move "During the strong dust ... can be neglected." to results section

Improved, but at some places in the uncertainty discussion in section 2 we need to mention already some dust results (from section 3) to make clear that other effects (caused, e.g., by anthropogenic or marine aerosols) are negligible and thus do not introduce uncertainties in this specific case with the enormous dust load.

page 5, line 25 Could you please explain why you chose a point 160 km East of Limassol over the sea as trajectory end-point? Is it because the trajectories ending over the island failed to capture the observed dust transport?

According to MODIS, the thickest dust plumes occurred east of Cyprus. For this area we computed the trajectories. We state that now more clearly in section 3. But, yes, the HYSPLIT trajectories were really bad for Limassol. We leave out to mention that to avoid any confusion here… The trajectories are just shown to provide an idea about the main dust advection path.

page 5, line 25 Do you mean between 8 and 9 UTC on 8 September? How do you know without lidar observations and radiosounding profiles at 6 and 12 UTC?

Yes, we mean 8 September, and we make the statement more specific (see section 3.1): The peak dust front reached Limassol *at ground* between 8–9 UTC on 8 September (see photographs below taken briefly after the arrival of the dust front). So, we know it from our own observation (by eye).

Technical corrections

We checked all the points (below) and corrected them (100%)

abstract Please provide full name for MODIS and EARLINET.
page 1, line 10 "close to 8000 _g/m3" or "near 8000 _g/m3"
page 1, line 21 remove ">"
page 3, line 8 change "belongs to" to "is part of"
page 3, line 16 remove last "and"
page 5, line 20 change "a coarse idea information" to "a rough idea" or "an impression"
page 5, line 22 _gure and caption give arrival height of 2.5 km, text gives 1.5 km for lower dust layer
page 5, line 23 add space after "(RH)"
page 5, line 20-25 I _nd it hard to follow this part due to a number of parentheses (and at least one too many if I'm not mistaken). Please rephrase, incorporating the information in parentheses in the text.
figure 5, caption change "at the roof" to "from the roof"
figure 6, caption move everything from "The AOTs are..." to main text
figure 6, map in panel c increase font size, it is very hard to read
page 8, line 15 "Kandler et al., 2011" in parentheses
page 9, line 4 use either "wrong visibility estimations" or "a wrong visibility estimation"
page 9, line 4 change "unusual very" to "very unusual" or just "unusual"
page 9, line 7-8 there is a verb missing after "... so that the..."
page 9, line 7 change "volumne" to "volume"
page 9, line 23 change "visbility" to "visibility"
page 9, line 31 change "oberved" to "observed"
page 10, line 17 change "A more ... pro_les" to "More ... profiles"
page 11, line 8 change "keeping" to "taking"
page 11, line 16 change "a variety optical" to "a variety of optical"
page 11, line 20 replace "strength" by "intensity"
page 11, line 27 change "improved" to "improve"
page 11, line 34 remove "profile"

Improved

References

Preißler, J., F. Wagner, S. N. Pereira, and J. L. Guerrero-Rascado (2011), Multi-instrumental observation of an exceptionally strong Saharan dust outbreak over Portugal, Journal of Geophysical Research: Atmospheres, 116, D24,204, doi: 10.1029/2011JD016527.

Included (Introduction section)

……

Reviewer #2 (minor revisons):

Minor comments and notes

• 3/29: 'The uncertainties in all the optical properties...': Here, one of the papers by Gasteiger and colleagues should be cited who performed a lot of quite detailed investigations on this topic (desert dust, volcanic ash).

We include both references in Section 2.1, … Gasteiger 2011a,b. The reviewer is right. There are not so many papers dealing with irregularly- shaped (desert or volcanic) dust. So, we should cite these two Gasteiger papers to stimulate even more modeling in this field.

• 4/12: '± 50': Unit is missing.

Improved

• 5/11: Fig. 1: Please mark Limassol in at least one of the panels

Done, in all panels Limassol is now indicated by a red point.

• 5/29: Why are the lidar measurements restricted to day-time measurements: lack of personnel? I assume the system does not run unattended?

We provide more information regarding the measurement time periods (section 3). But all the measurements were performed until about 21 UTC, … which is midnight in Cyprus! Nighttime observations were always performed to have at least 2-3 hours for Raman extinction profiling.

• 6/8: 'and 600 µg/m3...'. When averaging over 3 hours this is certainly a lower limit. From Fig. 3a it can be seen that during the first hour the concentration was significantly larger. So it was indeed a strong event!

We checked all this. We now present only mean values for 7 September 19-20 UTC (throughout the paper). And the mass concentrations for the 18-19 UTC (first hour) are not higher. After arrival of the dense dust layer below 1000m the signals above 1000m got strongly attenuated which gives the impression in the color plot of the range-corrected signals that there is less dust.

• 7/17: 'Therefore the area mean values...' What does this mean? Is it – due to the fact that the maximum retrievable values might be exceeded – sort of an estimate of the lower limit?

We explain the averaging procedure now in section 2 and section 3. We include all available data, even the ones set to 5.0 (which indicates..the true AOT was larger), in the averaging. That means, the computed area mean AOT value is clearly lower than the true area mean AOT. Even if we exclude the 5.0 values, the averaging would lead to underestimation, because we leave out to consider the high AOT values at all.

• 8/16: Paragraph starting with ’To check...’: I doubt that it is possible to determine a relationship between PM10 and TSP taking into account the uncertainties of the contributing variables/measurements (during this episode), and I don’t understand the message of the related discussion. The authors found an ’excellent agreement’ with Kandler’s values. On the other hand they present arguments against the assumed values (stating that either cv,d or rvis is wrong). If however rvis is wrong this would feedback to the estimated extinction coefficient and the mass concentration. Some additional explanations would be helpful to avoid possible confusion.

We simplified the text and reduced the information content in section 3. The only essential point is that Kandler et al. (2011) found that the total suspended particle (TSP) mass concentration is about a factor of 1.2-1.5 larger than PM10, which is quite reasonable because PM10 only considers particles with diameters < 10 µm. And when we combine our visibility observation of 500m (leading to TSP mass concentrations of 10000 micrograms per m3) and the in situ measured PM10 was 8000 micrograms per m3 then this is a good and reasonable match with the findings of Kandler et al. (2011). We state that. Afterwards we discuss the problems with the routine visibility observations at the airports and the large uncertainties is the estimated visibility values leading to large uncertainties…. In this way all the complex information is better organized, and will produce less confusions .

• 10/7: ’termine’: typo.

Improved

…………………………………………………………………………………………………….

Reviewer #3 (major revisons):

In general the authors replied to the majority of my comments adequately. However, I find that the discussion about the vertical distribution and the AOD on the 8th of September (the day with the heaviest dust load) is not convincing enough (see major comments for details). Although, I believe that the authors describe indeed an extreme event as indicated by the very low visibility and PM10 concentration during the 8th September, but I am not persuaded based on the observations that the AOD is larger than 5, while it can be 3 (of course the event is still extreme).That said I suggest again publication to ACP once the authors have taken into account the following comments.

Yes, we agree! Therefore, we simplified the discussion (following the suggestion of the reviewer) and discuss two scenarios, only. We assume a well-mixed dust layer up to 800 m or 1500 m. With an extinction coefficient of 6 km-1 at all heights we end up with AOTs of 4.8 to 9. These value corroborate the MODIS data, which suggest AOT>5.0. We feel that such a speculative discussion is tolerable in a case of such a unique dust storm. All this is consistent with the radiosonde observations (at least not in contradiction with the radiosonde profiles).

However, we do not use AOT estimations by assuming that the main dust clouds were within the lowest 300 m. This was the third scenario suggest by the reviewer. This gives unrealistically low AOTs (of the order of 2-2.5). On the other hand, we never observed such shallow dust layers with the EARLINET lidar over Limassol from 2010 to 2015…, or at other places with our lidars (Morocco, Cabo Verde, Barbados, Tajikistan, South Korea…). So, this appears too speculative.

Major comment

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 Agia Marina_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 agree! As a consequence, we used the AERONET data Agia Marina (30 k m west of Nicosia) and compared them with the MODIS observations (area mean, 50 km radius) for the full 7-12 September period. We found good agreement, when taking the suggest uncertainty of 0.15xAOT into account, and when we also took into account the orographic aspects (changing heights above sea level…. over the orographically detailed terrain in the area around Nicosia).

Then we tried to use Sede Boker AERONET data, but this did not work, there was a too low amount of quality-assured MODIS data… So, we checked the Weizmann Institute AERONET data, and were successful. Here are the findings for the Weizmann AERONET station:

8 Sep: MODIS: 5.0, AERONET: no observations

9 Sep: MODIS, 3.1 and 3.95, AERONET: 2.4-2.6

10 Sep: MODIS, 3.8, AERONET 2.4-2.8, and later … MODIS 2.9, AERONET: 2.0-2-4

Finally we checked the Limassol AERONET observations for the second largest dust storm (1 April2013)

MODIS: 4.5, AERONET 3.2-3.5 during the time of the overpass plus minus 30 minutes.

We briefly summarize these results regarding the MODIS uncertainties in section 2.2

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.

REPLY: Indeed, this is the expected uncertainty based on statistical comparisons with AERONET. However, here we have a specific event and as such MODIS AOD retrievals can be from very good to very bad. The comparison of MODIS with the lidar confirms the good performace of the retrieval when the AOD is about 1 or less. This is a useful addition to the paper. On the other hand the 8th September, there are not lidar observations to compare with. However, this appears to be the most important day of the event (at least close to the surface, where observations are presented) with high AOD based on the MODIS images (as the surface is not visible). As I said in my first review it is important to validate the MODIS retrievals for high AOD as the validation against AERONET (e.g. Levy et al., 2013) is mainly for AODs less than 1 and simply we do not know the performance of MODIS AOD for the extreme cases with AOD greater than 1 or 2.

We agree, the answer is given above!

Finally, the estimation of the AOD using the surface observations and extrapolated vertically based on the radiosonde is very uncertain regarding the thickness of the layer. Just looking at both the potential temperature and the relative humidity I would say that the thickness is 0.8 km and not 1.5 km used in text, while there is an inversion at ~0.3 km, which could also be the top of the dust layer. Note that the lowest value is in agreement with the lidar observations of the 9th September. On the other hand the value of 0.8 km multiplied with 6000 Mm-1 gives an AOD of 4.8, which is closer to the values reported by MODIS to Figure 6. Briefly the MODIS AOD image of the 8th September should be given and the retrievals should be validated against the AERONET observations for this day. Ideally, this should be done also for the other days of the event 7-11 September (but it is not necessary given the comparison with the lidar, although there is significant time difference between the lidar observations and MODIS AOD, while for AERONET the time difference can be less than 30 min).

We agree and follow the reviewer in section 3.1. However, we discuss the AOT in cases of well mixed layer up to 800m and up to 1500m as mentioned above (radiosonde discussion). There is no reason, to assume that a well-mixed layer up to 1500m is unrealistic. The radiosonde profiles are consistent with both assumptions. However, we need to be careful with the sonde profiles, the sondes were launched at Nicosia, more than 50km northeast of Limassol, and there was much less dust at Nicosia on 8 Sep, …. indicating weather conditions (and T and RH profiles) different from the ones at Limassol. We now explicitly say that we speculate here…

We leave out to discuss the third scenario (mentioned above). 300 m thick or shallow dust layers with huge dust extinction coefficients of 6 km-1 are simply too unrealistic, to our opinion. And if that was really the case, we are sure, that pilots of air planes landing at Larnaca around noon would have noticed that and would have reported that, … that there was a sharp shallow dust layer. But they just reported very low visibility of about 500m on 8 Sep during approaching the Larnaca airport and landing phase. This is in agreement with our visibility estimation (by using the phtographs). We leave out to mention the reports of the pilots (not needed).

Minor comments

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

We think, page 5 (not page 3) is meant! Now we provide a more relaxed discussion, following the way suggested by the reviewer in Sect.~3.1.

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

REPLY: As I explained in my previous reply to comment 5 I disagree that the lower layer is well mixed and up to 1500 m. This is a crucial point for the AOD estimation during this day.

What can we answer here! We understand the reviewer! But, it may be helpful to state in addition: Albert Ansmann (A.A., second author) launched more than 500 Vaisala radiosondes during lidar field campaigns during the last 20 years (lidar/radiosonde field sites), and feels experienced enough to interpret radiosonde profiles. For A.A. there is no doubt that the Nicosia sonde profiles corroborate well-mixed conditions up to 1500m on 8 September. This is clearly corroborated by the monotonic increase of RH up to 1500 m height of the 12 UTC sonde on 8 September. However, A.A. is careful enough not to trust the sonde profile data too much. We have to consider that the radiosonde data in the data base only show significant changes in the temperature and RH profiles (we would like to have the original profiles with very high vertical resolution), and that the launches were conducted far away from the lidar site and not exactly to the time when the sharp dust front crossed Cyprus, and differently in northern (Nicosia) and southern Cyprus (Limassol). This does not mean that we better avoid to use these radiosonde profiles. No! It means, we should just be very careful, and if we see consistency between lidar and radiosonde profile structures we should take that as an indication that the air mass characteristics seen by the radiosonde was obviously similar to the one above the lidar site.

But we got the point of the reviewer, and changed the discussion towards a more careful argumentation…

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.

We checked corresponding MODIS-based AOT maps and concluded not to follow the reviewer in this point. These maps will trigger new questions because it is simply not easy to provide a rather dense quality-assured AOT data sets over the Med Sea and over Cyprus (a very crucial island for satellite remote sensing, with mountains up to 2000m, with bright desert and dark forest surfaces…, etc). The suggested maps are however only useful if the data set is dense (not too many gaps). We estimated that we need one week to carefully check all available MODIS data to produce such an AOT map. And at the end, we will have many yellow areas (indicating AOT>5.0) in the southern parts of Cyprus and over the Med Sea (to the south). What does that help??? It makes everything too complicated. So, we leave out to produce such a map. Maybe MODIS 'enthusiasts' will be triggered by our article to do that….

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…

REPLY: Similarly to my reply to comments 5 and 12, I disagree about the thickness of the lower layer and the fact that it is well mixed. In any case I do not think that it is difficult for you to add one more figure to the paper with the MODIS AOD of the 8th September, especially from the moment that you have the data already. It is just 10 min work to create it.

10 minutes!!! We have the feeling we need much more time because we are not MODIS retrieval experts, and this map will then trigger new questions. And we do not think that such a map is needed. So, we leave out to present such a map.

New comments

1)Page 1, Lines 20-22 and Page 2, Line 1: These are your results, so I do not think that it appropriate to start the paper with them, so please delete them. If it's not the case provide the references.

We changed the text, but we need to start with the MODIS observations. We now analyzed MODIS observations from 2001-2015. These data allow us to immediately state that this 8 Sep 2015 dust storm was a unique event. We provide a reference for the MODIS data base and a new Fig. 1.

2)Page 2, Lines 6-7: "However … decade." Where this statement comes from?

This statement is now based on our 2001-2015 MODIS data analysis. The 8 September peak AOT is the largest of the last 15 years (see Fig.1).

3)Page 4, Line 5: "On 8 … exceeded." I think it is better to move this sentence to Section 3.

We changed this text part (section 2.2 on MODIS) completely. We provide an extended error analysis, including for cases with AOT>2.5.

4)Page 4, Line 12: "+/-50". I think the % is missing.

Improved

5)Page 4, Line 31 and Page 5, Lines 1-3: "During … neglected." These are results and are better suited for the Section 3.

No! In section 2.4 (on visibility observation) we discuss all error sources, and to make clear that we can neglect anthropopenic and marine aerosol contributions to the reduced visibilities, we need to provide the optical properties found during the reported dust storm.

6)Page 5, Line 20: Clearly, I do not see what the HYSPLIT model adds on the paper, especially from the moment that MODIS images show the origin and evolution of the dust plume and the starting point of the backwards trajectory is not Limassol.

The starting point is in a region with the densest dust plumes according to MODIS. We state that now. The HYSPLIT trajectories are just given (or better needed) to show the main air mass transport way. MODIS maps in Figure 1 do not show that so clearly.

7)Page 6, Line 1-2: Why you do not present radiosondes also for the other dates of the event 7-11 September? This will further corroborate the connection of the layering seen by the lidar and the radiosondes.

As mentioned several times above: The sondes provide a rough idea about the temperature und relative humidity profiles over Limassol. And our experience with sonde/lidar observations show that they are always in very good agreement. So, we do not think that we need the sonde profiles. Just to show that the RH and temperature profiles are in good agreement with the lidar profiles is not enough motivation for us to show them.

We usually like to show radiosonde profiles but in this case, we feel , it does not contribute much. And the radiosonde site is close to Nicosia, 70 km northeast of Limassol. This area was excluded from the main dust transport regime. Furthermore, the sondes were launched at 12 UTC or early, and our lidar observations are mainly done in the late afternoon and evening.

8)Page 6, Line 8: Replace “exceeded already” by “reach”.

Improved

9)Page 6, Line 18: AOT of what? The lidar? You have also the time series of MODIS in Figure 6.

Improved …… AOT from lidar and MODIS observations….

10)Page 6, Line 23: How the values of 8-10 km are estimated?

We took these data from the routine visibility observations at the three airports. But these are rough estimates. We changed the text … visibility > 10 km is a more save statement.

11)Page 7, Lines 2-9: In the model deficiences you are referring to cloud convection. However, in MODIS images there are not clouds in the source region.

The clouds can be found on MODIS maps of 7 September, east of the region shown in the old Figure 1 (now Fig.2, eight satellite maps) . This map (to the east) will be shown in the second paper on modeling (Solomos et al.).

12)Page 7, Line 25: Why there is not comparison of the lidar and MODIS the 7th September?

The dust changes are large on 7 September, and the MODIS results are given for morning and noon hours, and the lidar observations were done in the evening. A comparison is useless in this case.

13)Page 7, Lines 29-30: Once again, why you do not show the radiosondes?

We find that it is sufficient to provide the general radiosonde results here. We already stated several times why we do not show radiosonde data.

14)Page 7, Line 32: How the values of AOD for anthropogenic and marine aerosols are estimated?

From our own long-term lidar and AERONET studies at Limassol, and by other AERONET observations over remote Ocean sites. We provide references and more explanations now.

15)Page 11, Lines 17-18: “The highlight … observations.” Sorry to disappoint you, but the most important day of the event the 8th September, there are not lidar observations. So, this sentence is not justified, please delete it.

We changed the text accordingly

16)Page 11, Line 18: According to your reply to my comment 15, I do not think appropriate to call your lidar state-of-the-art. Please delete this characterization.

We removed ‘state-of-the-art’

17)Page 11, Line 22: “constellations” you mean “conditions”?

Improved

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, **Moderate Resolution Imaging Spectroradiometer**) 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 **(European Aerosol Research Lidar Network)** 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 exceeded values of 5.0 **according to MODIS** 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 **to** 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 mainly indicated 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) already 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 dense 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. **According to MODIS (Moderate Resolution Imaging Spectroradiometer), the aerosol optical thickness (AOT) exceeded 5.0 at 550 nm over large parts of the Eastern Mediterranean**. The dense dust clouds originated from Middle East deserts, mainly from northeastern Syria and northern Iraq. Such strong dust storms are rather seldom. **Figure 1 provides an overview of AOT observed with MODIS over Limassol, Cyprus, from 2001–2015. Twelve extreme dust outbreaks reached Limassol in southern Cyprus within the 2001–2015 period. The by far strongest were observed on 1 April 2013 (AOT $>$ 4.0, Saharan dust storm) and 8 September 2015 (AOT $>$ 5.0, Middle East desert dust storm).** 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 the Mediterranean. The AOT is most frequently lower than 1.5 during these events (Gkikas et al., 2016). An extended aerosol characteristics for the entire Mediterranean region and an extended literature survey is also given by Georgoulias et al. (2016).

Surprisingly, dust transport models widely failed to predict this record-breaking dust storm in September 2015 (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). **Another lidar study of an exceptionally strong dust outbreak with dust optical depth up to 2.0 towards Portugal was presented by Preißler et al. (2011)**. 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. 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, a.s.l.), Cyprus. The lidar station **is part of** 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), 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 $c_{\rm v,d}$ is $0.64\pm0.06\times10^{-12}$Mm.

The uncertainties in all the optical properties, conversion factors and estimated microphysical properties are discussed by Tesche et al. (2009a, b); Gasteiger et al. (2011a, b); Ansmann et al. (2012), and Mamouri and Ansmann (2014). Relative uncertainties in the dust backscatter and extinction coefficients and lidar ratios are 10–20% at dense dust conditions. Considering in addition a relative uncertainty of 10% in the assumed dust density $\rho_{\rm d}$ and of about 10% in the conversion factor $c_{\rm v,d}$, we yield an overall relative uncertainty of 20–30% in the estimated dust mass concentrations.

2.2 MODIS observations of AOT

MODIS 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. **For Limassol, we also calculated the mean AOT for a 25 km radius**. **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 >0 over land and over the Mediterranean Sea, respectively.** The maximum retrievable AOT is 5.0. **In the data MODIS base (https://ladsweb.nascom.nasa.gov/data/search.html.), all individual validated (pixel) AOT values are set to 5.0 for AOT≥5.0. As will be discussed Sect. 3, this was the case for several stations on 8 September 2015.**

The uncertainty in the retrieved AOT is $0.05\pm0.15\times$ AOT for AOT$\leq$1.0 (Levy et al., 2010, 2013). **Our comparisons of the MODIS products with available AERONET observations at Agia Marina (30 km west of Nicosia) corroborate this uncertainty for AOT<1.0. However, MODIS AOT values were systematically larger for AOT>2.5. We analyzed Limassol observations (1 April 2013, MODIS AOT of about 4.5, AERONET AOT of 3.2–3.6) and measurements over the AERONET station of the Weizmann Institute, Rehovot, Israel (9-10 September 2015, MODIS AOT of 3.8-3.9, AERONET AOT of 2.4-2.8). Overall, the AOT overestimation was in the range from 0.5–1.5 for AOT(550 nm)>2.5.**

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. **Uncertainties of the order of ±20–50% must be considered in the discussions of the observations in Sect. 3 as our analysis revealed**.

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)

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

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.

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, contributions of marine and anthropogenic particles (including contributions by water uptake) to the total particle extinction coefficient can be neglected. Under clear-air conditions, the extinction coefficient of urban haze at 500–550 nm is 50–150 Mm^{-1} over Limassol (Nisantzi et al., 2015). A typical marine aerosol contribution to particle extinction is 50–100 Mm^{-1} (Mamouri and Ansmann, 2016).

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))

$$M_{\mathrm{d}} = \rho_{\mathrm{d}} c_{\mathrm{v,d}} \sigma_{\mathrm{d}} \quad (3)$$

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. 2 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. Unfortunately, lidar observations were not possible on 8 September. We did not switch on the lidar on this day to avoid any potential damage of lidar optics and detection units. 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 on 7, 9–11 September.

To provide a rough idea about the dust source regions and the main airflow during this dust event, Fig. 3 shows six-day backward trajectories for 8 September 2015 (9 UTC). The arrival height of the red trajectory (500 m a.s.l.) is in the lower dust layer which reached to about 1.5 km height according to the Limassol lidar observations on 7 and 9 September. This is 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. The arrival height of the blue trajectory (2.5 km) is in the upper dust layer (from 1.5–3.8 km as seen by the lidar on 7 and 9 September and indicated by the Nicosia radiosonde profiles on 8 September). The backward trajectories are calculated for a site in the Mediterranean Sea, east of Cyprus (34.7°N, 35°E). Here, the densest dust plumes occurred in the Cyprus area according to Fig. 2 on 8 September 2015. 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 Cyprus.

Figure 4 presents the Limassol lidar observations of the vertical dust layering observed from 7-11 September 2015. **We operated the lidar daily for 3–11 hours up to about local midnight (21 UTC), except on 8 September**. **Dust advection occurred in two to three pronounced, separated dust layers (below about 500-800 m height, and two layers with top heights of 1.5–1.7 km and 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. **We speculate that these layer structures also prevailed on 8 September.** This is corroborated by the profiles of temperature and RH measured with radiosondes launched at Nicosia about 60 km northeast of Limassol on 8 September at 6 and 12 UTC.

The peak dust front reached Limassol **at ground** between 8–9 UTC on 8 September **(see photographs below taken briefly after the arrival of the dust front)**. The vertical gradients of temperature and RH were significantly different in the height ranges below and above 1.5 km height. The 12 UTC radiosonde 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 in the Nicosia area. 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 5 depicts the dominating two-layer dust structures in terms of dust mass concentration derived from the lidar observations in the evening of 7 September. The values reach 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, 2–3 hours before the 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.

Similar dust layering structures were then observed with lidar a day later on 9 September 2015 (see Figure 4), again in consistency with the temperature and humidity profiles of the Nicosia radiosonde (not shown). 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 2 km height. Traces of dust were however detected up to 3–4 km height. On 12 September, **the decrease in the AOT values derived from lidar and MODIS observations indicated the end of the dust episode**.

In Fig. 6, 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 to more than 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 **up to 800 m or 1.5 km, we end up with AOTs of 4.8 and 9, respectively. These speculative values are in the range of AOTs indicated by the biased MODIS observations.** Such huge dust optical depths indicate column dust loads of 8–15 g/m^2. In the upper layer (above 1.5 km height), 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. 2.

Figure 5 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, and 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 7a 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. The maximum retrievable AOT is 5.0. As mentioned in Sect. 2.2, many of the individual, validated (pixel) AOT values were set to 5.0 (indicating that the true values were larger). For Fig 7, we used all validated data points in the averaging. **Therefore, all area mean AOT values for 8 September (Julian day 251) exceeding 3.0 have to be interpreted with caution. They include many 5.0-AOT data and are thus biased (towards too low AOT). As outlined in the foregoing section, the uncertainty in the retrievable AOT values is about 0.05**$\pm 0.15 \times$**AOT for AOT**$\leq$**1.0. A systematic overestimation of the order of 1.0 must be taken into account for high AOT**$\geq$**2.5.**

The AOT clearly exceeded 4.0 in the eastern and southern parts of Cyprus on 8 September 2015, if we assume an AOT overestimation by 1.0. For Limassol, we also calculated the area mean AOT for a 25 km radius around Limassol on 8 September (blue diagonal cross with circle in Fig. 7). The area mean AOT of 4.9 includes many 5.0 values which indicate that the retrieved MODIS AOT clearly exceeded 5.0 over the EARLINET lidar station. It should be mentioned here that the mean AOT values were widely determined by the quality-assured values over the Mediterranean Sea (at all 5.0). Over land, the validated AOT values were significantly lower, mostly 3.0–3.5 on 8 September, 10:30–11:30 UTC. However, over the orographically inhomogeneous terrain, north of the coastal city of Limassol (with surface levels mostly varying between 200 and more than 700 m height a.s.l.), quality-assured data were rare.

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). Our lidar observations on 7 and 9–10 September reveal that the AOT contribution of the second layer above 1.5 km height was always of the order of 0.5. 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 550 nm, respectively **(Nisantzi et al., 2015; Mamouri and Ansmann, 2014)**.

Figure 7b 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 around 0 on 8 September which are mostly based on biased AOT values).

Figure 7c presents the surface observations of PM_{10} concentrations from 6-14 September 2015. Hourly mean values for five sites across Cyprus are shown. **Uncertainties are of the order of $\pm$50% for the sites of Larnaca, Limassol, and Pafos on 8 September 2015, and reduced to about 20% later on (9–11 September) according to the uncertainty analysis described in Sect. 2.3**. The maximum hourly mean dust mass concentration at Limassol was close to 8000 μg/m^3 on 8 September. **Note that the PM_{10} concentration was only 1300 μg/m^3 on 1 April 2013 (second largest dust storm during the last 15 years over Limassol in Fig. 1), because Saharan dust layers crossed Cyprus and Saharan dust is mainly transported within lofted layers as our EARLINET lidar observations show.** 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, which consider particles with diameters $<$10 μm only, 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 when density current-induced dust fronts cross the field site. 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). The visibility of 500 m according to Fig. 6 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, and thus in good agreement with the study of Kandler et al. (2011).**

To further 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 8 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 6 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. 2.4, marine and anthropogenic haze may have contribute to the total aerosol extinction coefficient by about 100–200 Mm^{-1} so that their contribution to observed extinction values exceeding 2000 or 3000 Mm^{-1} can be ignored in the following discussion and retrievals.

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 (Larnaca), 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 wrong visibility estimations (leading to a factor of 2 too low $r_{\rm vis}$ values) at these unusual 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 applied volume-to-extinction conversion factor of 0.64×10^{-12}Mm is roughly appropriate. **So we conclude that the visibility observations revealed too low visibilities at the unusual conditions on 8 September 2015.**

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 4 provides an overview of the main dust layering features and indicated mainly 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. 9, 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, visibility/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.

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 on 9–10 September. 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 on 9–10 September. 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 **determine** 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 according the evening lidar observations. Comparison with MODIS observations before and after noon is not possible on this day because of the rapidly changing dust conditions.

On 9 September, the 532 nm AOT decreased strongly from the record-breaking values >5.0 on 8 September to values of 0.55 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 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 late evening 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. 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 10 km in the evening of 9 September, which corresponds to particle extinction coefficients of about 300 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 a mixture of dust and urban haze).

An overview of the vertical dust mass distribution, observed in the evenings of 7, 9, 10, and 11 September 2015, is given in Fig. 10. In Eq. (1), we used a typical Middle East lidar ratio of 40 sr (Mamouri et al., 2013). 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 $\mu g/m^3$ 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. 10), 0.35 g/m^2

(9 September), 0.95 g/m^2 (10 September), and 0.6 g/m^2 (11 September). AOTs of 4.8–9 as estimated for the peak dust front on 8 September indicate peak column dust loads of 8–15 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. 10). The Limassol evening PM_{10} values (considering dust and aerosol pollution) were 55 μg/m^3 (7 September), 120 μg/m^3 (9 September), 125 μg/m^3 (10 September), and 165 μg/m^3 (11 September). The respective lidar-derived total aerosol mass concentrations were 65 μg/m^3 (7 September), 180 μg/m^3 (9 September), 125 μg/m^3 (10 September), and 290 μg/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 **taking** the uncertainties in the derived values into account. Horizontally inhomogeneous downward mixing of dust and horizontal inhomogeneities in the mixture of dust and urban pollution may have also contributed to the differences. Note, that Fig. 10 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 μg/m^3 (7 and 10 September) and 40–50 μg/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 of optical and microphysical, and dust layering properties obtained by means of very different in situ and remote sensing observational techniques and retrieval approaches. The presented documentation of an extreme dust storm 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 **intensity.**

Such unique events may take place once in a decade or even less frequently and are thus obviously linked to unique meteorological **conditions**. 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 improve 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 into 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 with an uncertainty of 20-30%.

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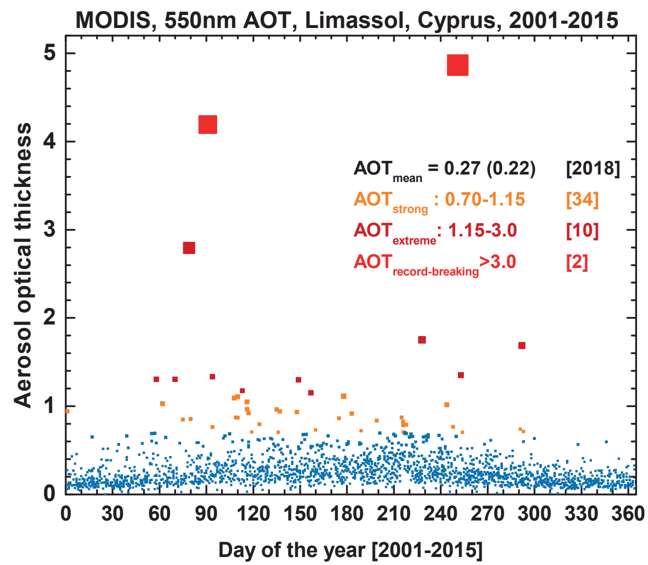

Figure 1. Seasonal distribution of 550 nm AOT at Limassol based on 15 years of MODIS observations (http://lance-modis.eosdis.nasa.gov/, terra MODIS, 2001–2002, aqua MODIS, 2003–2015). The mean AOT for an area centered at Limassol with 25 km radius is shown. Numbers (in black) indicate total number of considered daily observations (in brackets), the 15-year mean AOT (M), the standard deviation (SD, in parentheses), strong dust events (AOT from M+2SD to M+4SD), extreme dust events (AOT from M+4SD to 3.0), and record-breaking dust events (AOT>3). MODIS collection-6 data were used for the years 2005-2015 and collection-51 data for 2001-2004. More details to the MODIS data including AOT retrieval uncertainties are given in section 2.2.

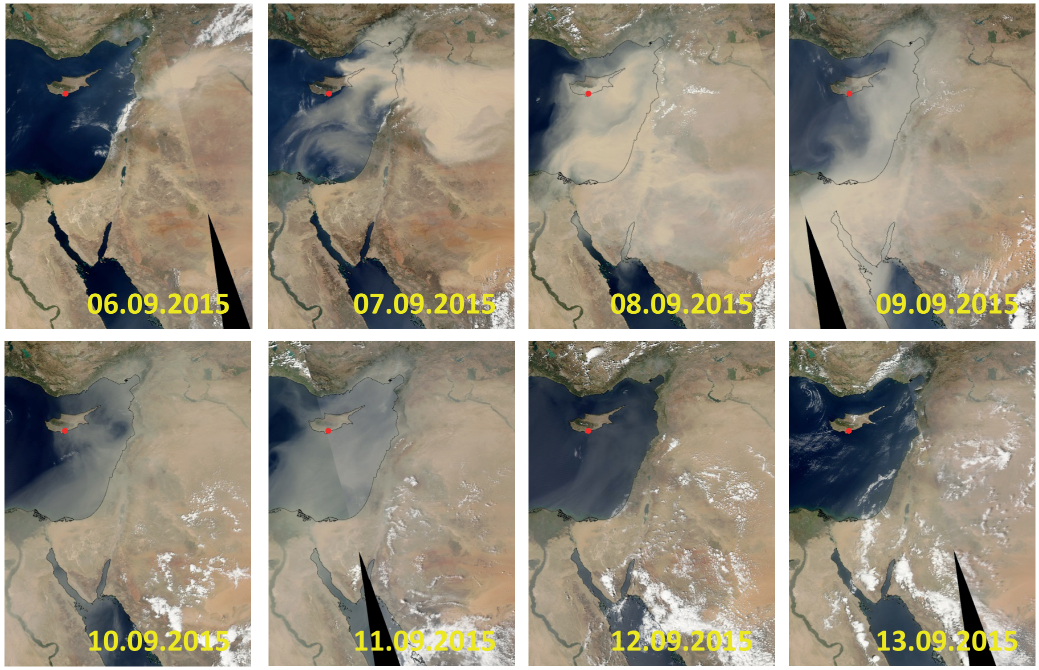

Figure 2. Dust outbreak towards Cyprus in September 2015 as seen from space (aqua-MODIS, 10:30-11:30 UTC overpasses, 13:30–14:30 EEST, Eastern European Summer Time). **Red points indicate Limassol.**

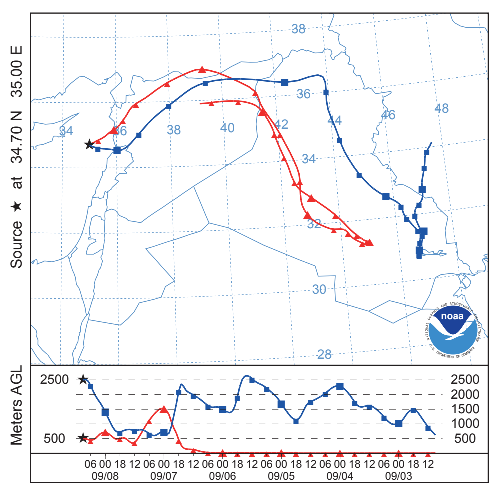

Figure 3. Six–day HYSPLIT backward trajectories (http://www.arl.noaa.gov/HYSPLIT.php) arriving in the Cyprus region at 35°E (about 160 km east of the Limassol lidar station) at 500 m (red, lower dust layer) and 2500 m height (blue, upper dust layer) on 8 September 2015, 09:00 UTC (12:00 EEST).

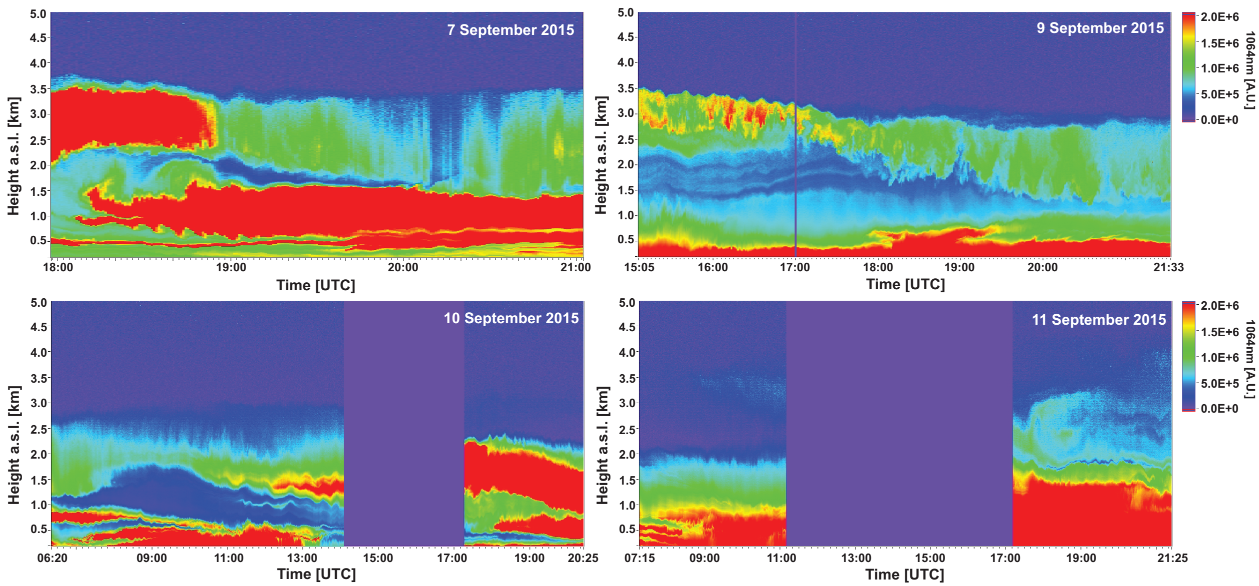

Figure 4. Desert dust layers observed with lidar over the EARLINET station of Limassol, Cyprus, on 7, 9, 10, and 11 September 2015. Range–corrected 1064 nm backscatter signals (in arbitrary units, A. U.) are shown. On 7-10 September, a two-layer structure dominated with dust layers below about 1-1.7 km height and another layer reaching to 2.5-3.7 km height. Local time (EEST) is time in UTC plus 3 hours.

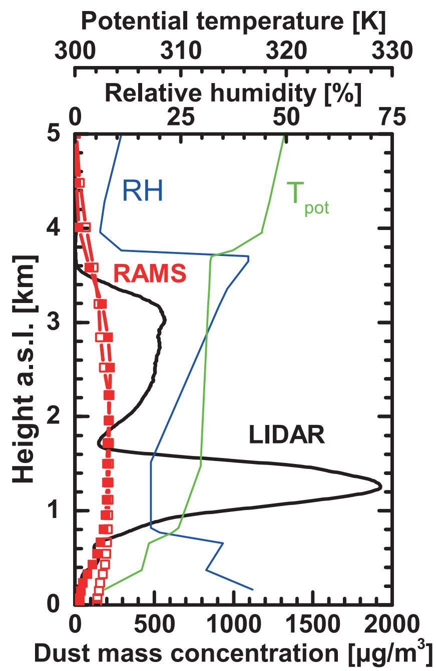

Figure 5. Mean dust mass concentration observed with lidar (thick solid black line) at Limassol on 7 September, **19:00–20:00 UTC**, and dust profiles simulated with RAMS (normal run with 20 km horizontal resolution) for Limassol, on 7 September, 18:00 UTC (closed red squares), and 8 September, 9:00 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.

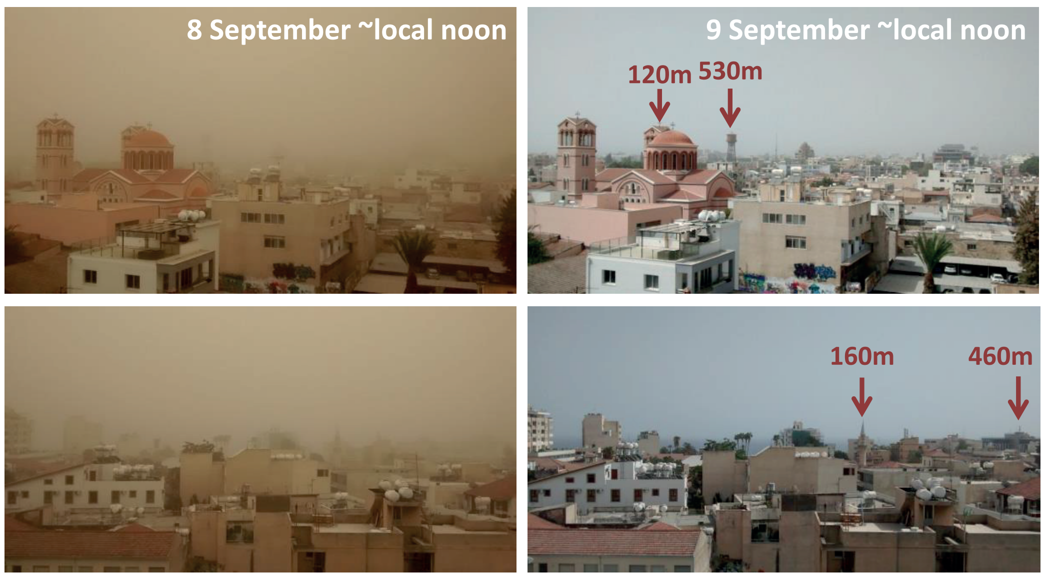

Figure 6. Photographs taken **from** the roof of a high building (CUT-TEPAK AERONET site) in the city center of Limassol to the north (top) and south (bottom) on 8 September 2015, 8:20-8:30 UTC (left) and on 9 September 2015 (right), again around local noon. The meteorological optical range (or horizontal visibility) was about 500 m on 8 September and $\geq$10 km on 9 September 2015. Distances to several towers from the AERONET station are indicated.

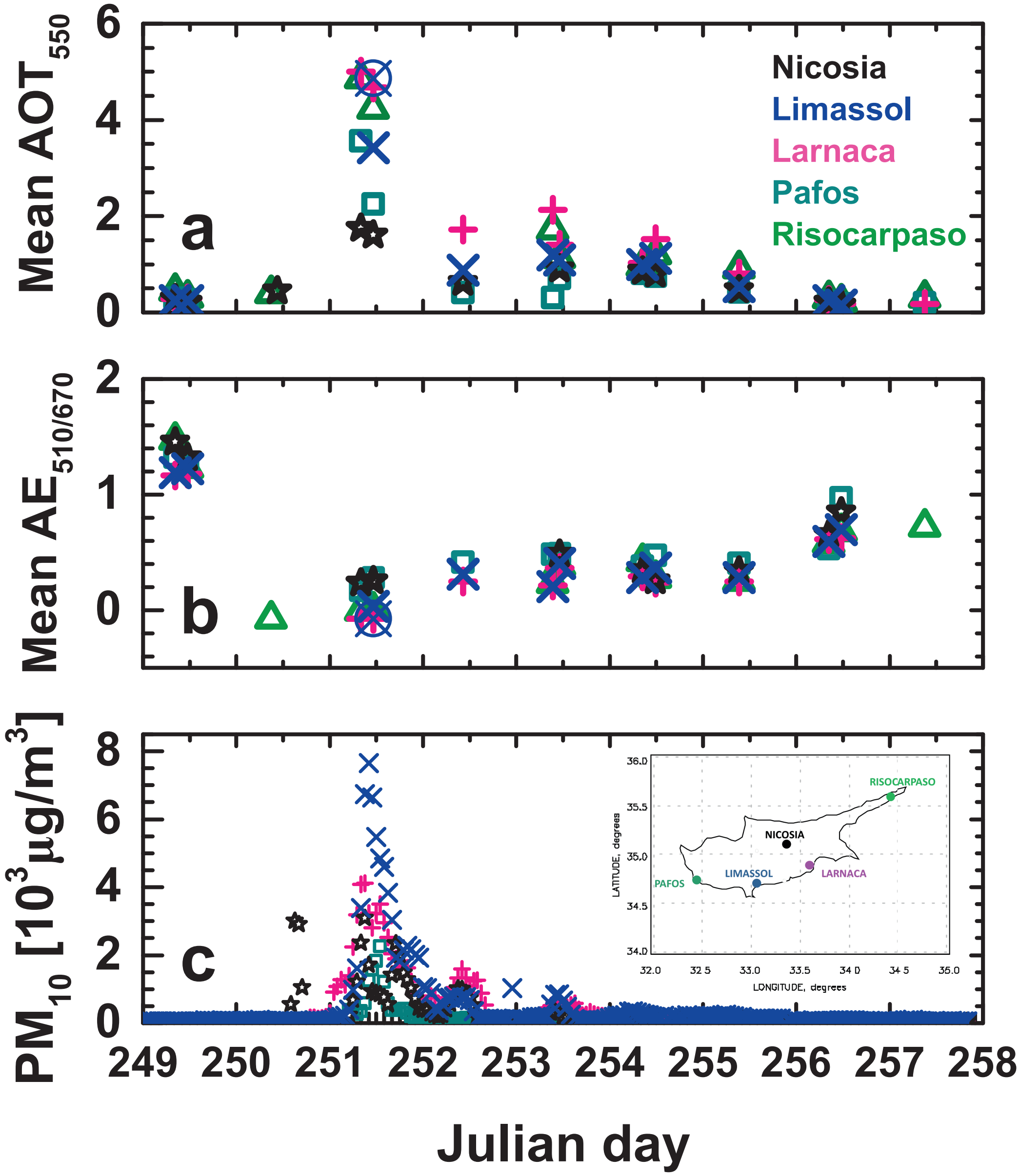

Figure 7. (a) MODIS-derived mean 550 nm aerosol optical thickness (AOT) for five sites in Cyprus for the period from 6-14 September 2015 (Nicosia, stars, Limassol, diagonal crosses, Larnaca, crosses, Pafos, squares, Risocarpaso, triangles, aqua-MODIS, 10:30-11:30 UTC, and terra-MODIS, 8:00–9:00 UTC overpasses), (b) MODIS-derived Ångström exponent (for the 510–670 nm 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 city, except the AOT indicated by the blue diagonal cross with circle (Limassol, 25 km radius, day 251).**

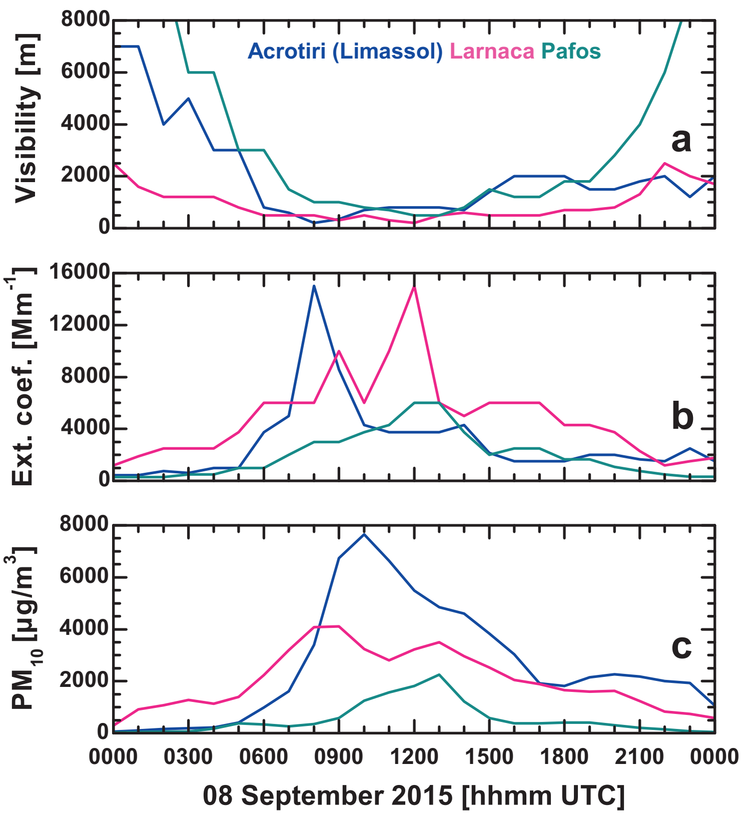

Figure 8. Visibility (r_{vis} in Eq. (2)) measured at three airports in southern Cyprus (see map in Fig. 7c) on 8 September 2015, (b) corresponding dust extinction coefficient (by using Eq. (2)), and (c) PM_{10} concentrations (same as shown in Fig. 7c). Relative uncertainties in all parameters are of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

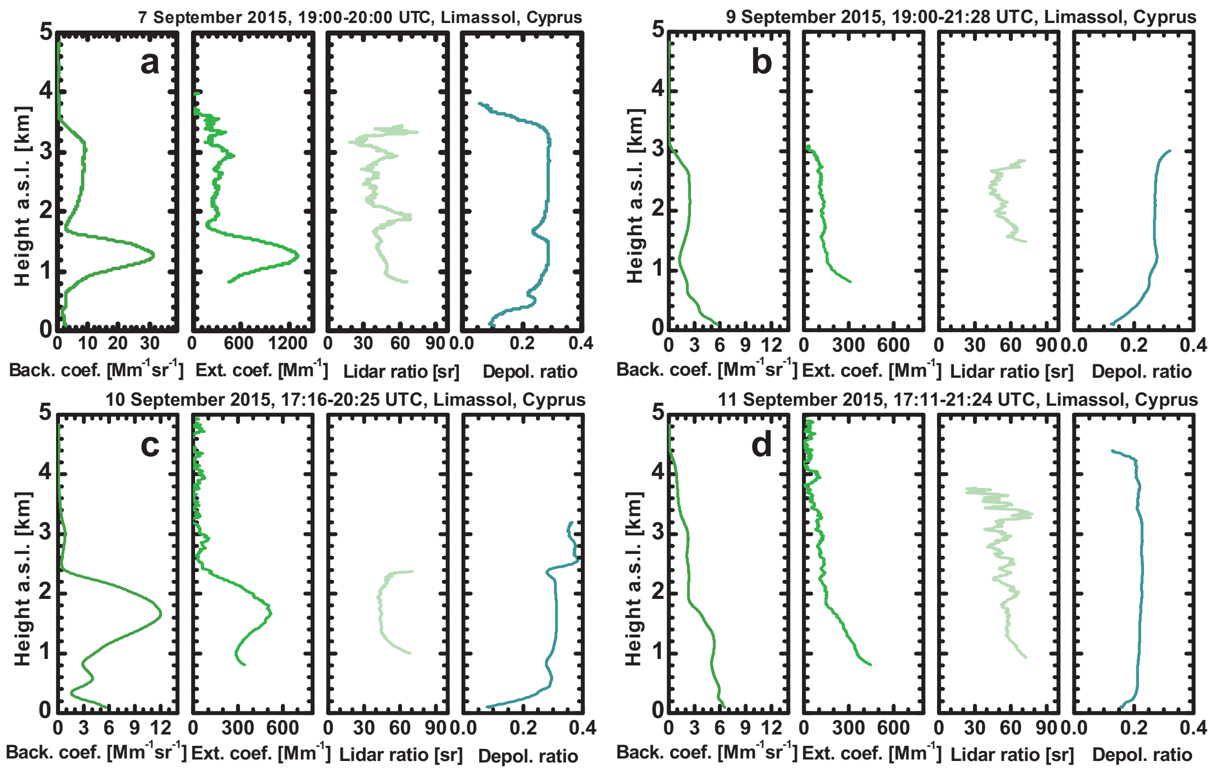

Figure 9. Mean vertical profiles of the 532 nm particle backscatter coefficient, extinction coefficient, lidar ratio, and particle linear depolarization ratio for the observational periods given on top of the panels on 7–11 September 2015. The Raman lidar method is applied. Retrieval uncertainties are of the order of 10% (backscatter coefficient, depolarization ratio) and of 20% (extinction coefficient, lidar ratio) at dense dust conditions.

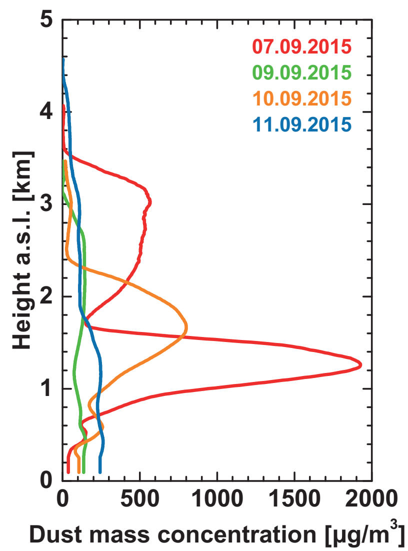

Figure 10. Lidar-derived mean dust mass concentrations for the evening periods (see Fig. 9) of 7 September (19:00–20:00 UTC), 9 September (19:00–21:28 UTC), 10 September (17:16–20:25 UTC), and 11 September (17:11–21:25 UTC). The overall uncertainty in the retrieval of the dust mass concentration is of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