Anonymous Referee #2

The paper entitled "3D evolution of Saharan dust transport towards Europe based on a 9-year EARLINET-optimized CALIPSO dataset" is an interesting analysis of mineral dust properties above North Africa, the Mediterranean and Europe that contains valuable information in 3 dimensions using CALIPSO products improved with EARLINET techniques and data. However, the manuscript needs to undergo some improvements before being published in ACP.

[REPLY] We thank the reviewer for the thorough revision and comments. Replies to the general and specific comments follow below.

<u>**General comments**</u>

First, I suggest to improve the English and writing throughout the manuscript.

[REPLY] We have revised the manuscript for language issues.

Additionally, results presented here are valuable and interesting but in general discussion need to be extended and completed at some points in Section 3. I suggest that the authors include more statistics such as the mean, standard deviation, extreme values, etc for some of the properties presented here and for the different regions.

[REPLY] We thank the reviewer for his suggestion. We revised Section 3 by including the discussion of DOD statistics (mean, standard deviation and extreme values - Section 3.1), the dust heights (standard deviations of CoM and TH – Section 3.2) and statistic on the extinction coefficient values (mean and Standard deviation - Section 3.3). The new discussions are the following:

Page 9, lines: 27: "More specific, during JFM (Figs. 1a, b) limited dust activity is observed almost uniformly over the Sahara desert. The DOD remains roughly over the entire study domain below 0.13 with 75% of the observations having DODs < 0.17, 95% of the observation having DODs < 0.5 and extreme values with DODs ~2."

Page 10, lines 1: "In the domains between 10° E - 30° E and 30° N - 40° N, 5% of the dust events are observed with DODs > 0.41, 1% with DODs >0.95 and extreme observations with DODs are up to 1.6."

Page 10, lines 7: "During AMJ (Figs 1c, d) dust production occurring over the entire Saharan desert with mean DOD values of 0.26 ± 0.26 and occurrences of 86%, uniformly at latitudes between 20° N and 30° N."

Page 10, lines 16:" In the domain between 10° W - 00° and 20° N - 35° N, the mean DOD is 0.43, with 25% of the dust observations having DODs > 0.69, 5% >1.2 and the extreme DODs up to 3 (Table 2)."

Page 10, lines 20 : "In the domain between 10° W - 00° and 35° N - 45° N, the mean DODs are 0.09 ±,0.14 with 5% of the dust observations having DODs >0.55 and extremes DODs up to 2.3."

Page 11, lines 16: “During JFM dust resides in general below 3 km a.s.e. (above surface elevation) over land with CoM at about 1.3 ± 1.6 km a.s.e. (Figs. 3a, b). Over the sea, several transport paths are discernible especially over eastern Mediterranean with dust tops traveling at 2.3 ± 1.9 km a.s.e. During AMJ, TH and CoM are up to 4.2 ± 1.7 $km$and around 2.4 ± 1.1 km a.s.e. respectively over eastern parts of Sahara.”

Page 11, lines 26: “This pattern leads to elevated dust at 3.0 ± 1.7 km a.s.e. and CoM at 1.6 ± 1.1 km a.s.e. over south European countries and Balkans. During OND the horizontal pattern is similar to JJA however with much lower heights (Figs. 3g, h).”

Page 13, lines 10: “Above the Balkans and during JFM values of 29 ± 65 Mm^{-1} are observed in the first 1.5 km, and 10 ± 30 Mm^{-1} between 2.5 – 3.5 km. In AMJ and JAS respectively, means of ~ 16 ± 40 Mm^{-1} and ~ 9 ± 20 Mm^{-1} are observed in altitudes between 1.5 to 5 km. The values of Clim-DE are higher (>45 Mm^{-1}) over Africa during winter and spring, in relation with the ones observed during the other two seasons (<45 Mm^{-1}) and reach high altitudes (5-6 km a.s.l.) during spring and summer. In summary, the obtained cross-sections for the five longitudinal zones indicate that higher extinction coefficient values are observed near the source and at low altitudes, where dust particles are efficiently deposited. Above NE Africa, the Clim-DE values are >45 Mm^{-1} throughout the year in altitudes up to 2 km a.s.l. during JFM and up to 4 km during AMJ and JJA. Moreover, the standard deviation of the means is around 130% at the altitudes up to 2 km and ~100% between 2 – 4 km, at all seasons. Above West Africa, the extreme Clim-DE values observed during JAS in the altitudes up to 2 km are 113 ± 131 Mm^{-1}. In C-E Mediterranean, dust is always present, with maximum extinctions during AMJ, reaching 27 ± 54 Mm^{-1} close to the surface and ~ 18 ± 30 Mm^{-1} during JAS and OND. In C-W Mediterranean, the highest means of JAS are ~16 ± 40 Mm^{-1}. For latitudes greater than 45° N, and during AMJ mean values of 8 ± 27 Mm^{-1} are 4 ± 16 Mm^{-1} are observed close to the surface above NE Europe and NW Europe respectively.”

Some sentences comparing the results obtained in Section 3 with results obtained in previous studies would also be useful.

[REPLY] We revised Section 3 by including discussion on the comparison of the results obtained in this work with results in previews studies (Papayannis et al. 2008; Balis et al. 2012; Mona et al. 2014). In section 3.2 we included a comparison with the dust plume heights documented by EARLINET. In Section 3.5 we included comparison of our trend with other studies over the same domain (Floutsi et al. 2016; Gkikas et al. 2013; Yoon et al. 2012; Georgoulias et al. 2016b). The new sections are:

Page 11, line 29: “In general, our results are in agreement with lidar-based studies which have been performed in several European sites. Papayannis et al. (2008) performed an exhaustive analysis on Saharan dust particles over Europe using EARLINET lidar profiles. They found that the dust layer center of mass extends from 3.0 to 3.8 km and the thickness ranges from 0.7 to 3.4 km. Specifically, Balis et al. (2012) calculated the mean base and top of dust layers in the eastern Mediterranean, Thessaloniki, to be around 2.5 ± 0.9 km and 4.2 ± 1.5 km, respectively. More recently, Mona et al. (2014) analyzed a long dataset of Saharan dust intrusions over Potenza, Italy, and found a mean layer centre of mass of 3.5 ± 1.5 km.”

Page 15, line 29: “In comparison with studies relevant to the time period considered in this work, the DOD decrease of 0.001 yr^{-1} over the northern coast of Africa is in agreement with Floutsi et al. (2016), who based on 12 years of MODIS-Aqua observations (2002-2014) reported an average decrease of 0.003 yr^{-1} for the coarse mode fraction of AOD over the broader Mediterranean Sea. Furthermore, over the same domain the decreasing trend of DOD coincides with the decrease of Saharan desert dust episodes as reported by Gkikas et al. (2013). Regarding the AERONET stations over the domain of northern Africa and Europe, Yoon et al. (2012) reported on the trends of AOD at 440 nm along with the corresponding Ångström Exponents (440 and 870nm). The documented negative trends over the AERONET stations of Avignon (France), Dakar (Senegal) and Ispra (Italy) are in agreement with the negative DOD reported here, although with discrepancies in the magnitude, while trend disagreements are observed over the AERONET station of Banizoumbou (Niger). The decreasing trends of DOD observed over the domain northern of Africa and Europe coincide with the generally documented downward AOD trends reported based on several satellite observations of MODIS/Aqua, MODIS/Terra, MISR and SeaWiFS (Pozzer et al., 2015; de Meij et al., 2012; Hsu et al., 2012; Georgoulias et al. 2016b). More particular, in the most recent study of Georgoulias et al. (2016b), using MODIS/Terra and MODIS/Agua observations, they reported negative statistically significant trends over Algeria, Egypt and the Mediterranean and positive trends over Middle East. Overall, for the Mediterranean they reported an AOD trend of -0.0008 yr^{-1} for the MODIS/Terra observations (2000 – 2015) and -0.0020 $yr^{-1}$for the MODIS/Aqua observations (2002 – 2015), with the trends being statistical significant at the 95% confidence level in both cases.”

They should also consider the use of tables to summarize main results, making easier for the reader to focus on the main findings of the study.

[REPLY] We introduced a new Table 2 where we summarize main results for different regions and seasons. We agree with the reviewer that this will help the reader to focus on our main findings. The new Table 2 is (page 37):

Table 2: Regional statistics on mean dust optical depth, max values, dust layer center of mass (CoM) and top height (TH) (a. s. e.), ratio of dust observations to cloud-free observations, ratio of cloud-free observations to total observations and domain boundaries.

	DOD Mean ± St.dev.	DOD Max Vals. (Perc. 95%)	CoM ± St.dev.	Top Height ± St.dev.	Nr Dst in Nr cl-free	Nr cl-free in Nr obs.	Domain
NE Africa							
JFM	0.11 ± 0.17	2.19 (0.42)	1.5 ± 1.2	2.6 ± 1.8	0.72	0.84	[10E,30E] [20N,30N]
AMJ	0.26 ± 0.26	3.09 (0.73)	2.4 ± 1.1	4.2 ± 1.7	0.86	0.86	
JAS	0.18 ± 0.21	2.63 (0.56)	2.3 ± 1.0	4.0 ± 1.4	0.84	0.93	
OND	0.11 ± 0.14	2.93 (0.34)	1.9 ± 0.9	3.3 ± 1.4	0.81	0.93	
NW Africa							
JFM	0.13 ± 0.18	1.86 (0.47)	1.5 ± 1.3	2.4 ± 1.8	0.67	0.82	[10W,10E] [20N,35N]
AMJ	0.26 ± 0.26	2.31 (0.75)	2.2 ± 1.2	3.8 ± 1.6	0.86	0.83	
JAS	0.43 ± 0.39	3.03 (1.20)	2.9 ± 1.0	5.1 ± 1.3	0.94	0.88	
OND	0.22 ± 0.26	2.59 (0.71)	2.2 ± 1.0	3.9 ± 1.6	0.82	0.81	
C-E Med.							
JFM	0.09 ± 0.18	1.62 (0.41)	1.3 ± 1.4	2.3 ± 1.9	0.69	0.70	[10E,30E] [30N,45N]
AMJ	0.12 ± 0.20	2.74 (0.51)	1.8 ± 1.5	3.2 ± 2.1	0.82	0.76	
JAS	0.08 ± 0.12	1.80 (0.33)	1.6 ± 1.1	3.0 ± 1.7	0.89	0.96	
	0.08 ± 0.11	1.55 (0.31)	1.4 ± 1.1	2.7 ± 1.6	0.82	0.80	

OND							
C-W Med. JFM AMJ JAS OND	0.03 ± 0.06 0.05 ± 0.10 0.09 ± 0.14 0.05 ± 0.09	1.09 (0.11) 1.35 (0.25) 2.33 (0.36) 1.62 (0.20)	1.3 ± 1.6 1.8 ± 1.6 1.9 ± 1.2 1.3 ± 1.2	2.0 ± 1.9 2.9 ± 2.2 3.3 ± 1.8 2.3 ± 1.6	0.49 0.65 0.75 0.63	0.57 0.61 0.80 0.64	[10W,10E] [35N,45N]
NE Europe JFM AMJ JAS OND	0.025 ± 0.055 0.033 ± 0.062 0.032 ± 0.045 0.023 ± 0.043	0.97 (0.11) 1.61 (0.12) 0.90 (0.11) 0.50 (0.09)	1.2 ± 1.4 1.6 ± 1.2 1.6 ± 1.1 1.2 ± 1.0	1.7 ± 1.7 2.5 ± 1.6 2.7 ± 1.4 1.9 ± 1.4	0.37 0.61 0.60 0.49	0.28 0.47 0.58 0.43	[10E,30E] [45N,60N]
NW Europe JFM AMJ JAS OND	0.015 ± 0.033 0.023 ± 0.037 0.022 ± 0.042 0.018 ± 0.035	0.47 (0.06) 0.73 (0.08) 0.93 (0.08) 0.57 (0.07)	1.2 ± 1.6 1.5 ± 1.6 1.4 ± 1.5 1.1 ± 1.2	1.7 ± 1.7 2.2 ± 1.9 2.1 ± 1.7 1.7 ± 1.4	0.36 0.52 0.43 0.40	0.36 0.47 0.52 0.44	[10W,10E] [45N,60N]

<u>Detailed comments</u>

I suggest to replace the word utilize by use

[REPLY] It is replaced throughout the manuscript.

Page 2, line 26: Replace “means of identifying” by “mean of identifying”

[REPLY] It is replaced.

Page 2, line 29: Remove “a” before pure dust extinction

[REPLY] It is removed.

Page 2, line 31: Replace later by latter

[REPLY] It is replaced.

Page 3, line 17-18: Is the climatology by Winker et al, 2013 on dust properties? If not, remove it from the paragraph

[REPLY] We changed the sentence in order to clarify the contribution of this study:

Page 3, line 24: “Moreover, Winker et al. (2013) provided a 3D global aerosol climatology from five-year CALIPSO data, along with the global distribution of mineral dust, derived using the ratio of columnar dust AOD to total AOD.”

Page 4, line 24: Replace CALISPO by CALIPSO

[REPLY] It is corrected.

Page 4, line 27: Explain the acronym LIVAS

[REPLY] We added the acronym’s explanation:

Page 5, line 3: “This product is a prominent outcome from the EARLINET-ESA collaboration for the LIVAS database (LIdar climatology of Vertical Aerosol Structure for space-based lidar simulation studies; Amiridis et al., 2015)”.

Page 5, line 5: Did you quantify this error? Could you provide an estimated value here?

[REPLY] We added the information in this sentence:

Page 5, lines 13: “During SAMUM 1 and 2 campaigns Saharan dust δ_{nd} values varied between 0.27 and 0.35 at 532 nm (Ansmann et al., 2011), introducing 4% error in our calculations for the dust separated backscatter values.”

Page 5, line 6: I suggest replacing “Based on this this technique” by “On using this technique”

[REPLY] The sentence is rephrased.

Page 5, line 31: I suggest starting a new paragraph from “The conditional dust product: : :”

[REPLY] Done.

Page 6, line 9: What do you mean they should be used with caution? Because of the definition provided here, it is expected that Con-DE is larger than total extinction for some cases, but it is still correct

[REPLY] This sentence has been removed from the revised manuscript.

Page 6, lines 11-16: It will be useful to include in this paragraph the information about the region studied and the period covered

[REPLY] We changed the first sentence as:

Page 8, line 21: “In Sect. 3.1 - 3.4, we examine the inter-seasonal variation and intensity of dust transport patterns, from 2007 to 2015, for the domain 20° W to 30° E and 20° N to 60° N.”

Page 6, line 28: Remove “of the” before “mean DOD values”

[REPLY] It is removed.

Page 6, line 30: Please add a short sentence here explaining why dust transport is suppressed

[REPLY] We added the sentence:

Page 9, line 26: “During autumn and winter the emission and transport of dust towards Europe is suppressed due to the more effective removal processes and due to the atmospheric dynamics favouring the transport of dust towards the Atlantic (e.g. Israelevich et al., 2002; Schepanski et al., 2009).”

Page 7, line 17: Provide the precise value of the mean DOD and its standard deviation instead of ranges or rephrase the sentence

[REPLY] We rephrased the sentence:

"Mean DOD over these areas reaches values of 0.12 ± 0.20 (Fig. 1d) and extreme observations observed with DODs up to 2.74."

Page 8, line 4: Does represent the total aerosol extinction or the dust aerosol extinction?

[REPLY] It represents the dust extinction. We improved the sentence: "α denotes the dust extinction coefficient at altitude z."

Page 8, line 22: Replace "situation" by "horizontal pattern" or "horizontal distribution"

[REPLY] We rephrased as:

Page 11, line 27: "During OND the horizontal pattern is similar to JJA however with much lower heights (Figs. 3g, h)."

Page 8, line 24: I suggest renaming section 3.3. as "Climatological dust cross sections" to be coherent with the title in section 3.4.

[REPLY] It has been replaced.

Page 9, line 3: what do you mean by mobilization of the sources here? Please, elaborate more this sentence

[REPLY] We changed the sentence as:

Page 13, line 13: "The spring and summer peaks indicate the increased activity of Saharan dust sources (Moulin et al., 1998; Schepanski et al., 2007)."

Figure 3 (4, and 5): Please, increase the size of the axis labels text for the Domain figures

[REPLY] The label size is increased and, now, it is more visible in the new version of the manuscript.

Page 9, line 12-13: Elaborate this sentence

[REPLY] We changed the sentence accordingly:

Page 12, line 23: "A steep decrease in extinction values is observed along the African coastline with values of 20 Mm^{-1} above the southern part of the Iberian Peninsula (38°-42° N) where dust is trapped by the Pyrenees. The distinct decrease of extinction values across the African coastline is an indication that dust is always present inside the rather deep Saharan boundary layer while it is only occasionally transferred towards the Mediterranean when atmospheric dynamics favor this kind of flow."

Page 9, line 15: Similar Clim-DE values are observed between 50-60 deg N for other longitudinal zones, why do you point it out for this specific zone? Also, what is the uncertainty for the Clim-DE product? Values of 5 Mm-1 are very low and could fall within the uncertainty. Add discussion regarding the uncertainty throughout the manuscript where needed

[REPLY] We changed the sentence:

Page 12, line 27: "At higher latitudes, the CALIPSO dust extinction is drastically reduced but still observed in ranges of 1-2 km a.s.l. and with mean Clim-DE values of 5 Mm^{-1}."

In Clim-DE and Cond-DE products, the uncertainty of the dust extinction values close to the surface and at high latitudes are < 54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values is < 20%. We added this in the manuscript in the new section 2.4 addreses the uncertainties of the product:

Page 7, line 26: "In general, Clim-DE and Cond-DE products, the uncertainty of the dust extinction values close to the surface and at high latitudes is < 54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values is < 20%."

Page 9, line 16: What are the criteria to consider a value of 10 Mm-1 "significantly"high?

[REPLY]. We removed this statement. The sentence now reads:

Page 12, line 28: "Moving eastwards (0°-10° E) elevated dust is trapped topographically by the Alps (47°-52° N) with values >10 Mm^{-1}."

Page 9, line 29-33: You should consider adding here more discussion and some statistical parameters (e.g. mean, standard deviation, maxima, minima, etc) to enrich this summary. Also, some sentences about the dust vertical distribution in the summary are missing.

[REPLY] Detailed statistics and have been added in our manuscript. The discussion about dust vertical distribution has been also extended:

Page 13, line 14: "In summary, the obtained cross-sections for the five longitudinal zones indicate that higher extinction coefficient values are observed near the source and at low altitudes, where dust particles are efficiently deposited. Above NE Africa, the Clim-DE values are >45 Mm^{-1} throughout the year in altitudes up to 2 km a.s.l. during JFM and up to 4 km during AMJ and JJA. Moreover, the standard deviation of the means is around 130% at the altitudes up to 2 km and ~100% between 2 – 4 km, at all seasons. Above West Africa, the extreme Clim-DE values observed during JAS in the altitudes up to 2 km are 113 ± 131 Mm^{-1}. In C-E Mediterranean, dust is always present, with maximum extinctions during AMJ, reaching 27 ± 54 Mm^{-1} close to the surface and ~ 18 ± 30 Mm^{-1} during JAS and OND. In C-W Mediterranean, the highest means of JAS are ~16 ± 40 Mm^{-1}. For latitudes greater than 45° N, and during AMJ mean values of 8 ± 27 Mm^{-1} are 4 ± 16 Mm^{-1} are observed close to the surface above NE Europe and NW Europe respectively."

Page 10, line 1: How is the impact on cloud formation estimated?

REPLY] The impact of dust on cloud formation is part of a second study we are working on. In this forthcoming work, we will use dust profiles from CALIPSOand EARLINET parameterizations to calculate the dust mass concentration for particles with radius greater than 250 nm and to estimate ice nuclei concentration profilesfollowing the technique provided by Mamouri and Ansmann (2016). We removed this sentence from the revised manuscript to avoid confusion.

Page 10, line 2: Please, include additional information and discussion on this part related to the dust mass concentration calculation. What is the point of calculating it here?

[REPLY] This sentenced has been replaced by:

Page 13, line 23: "The dust mass concentration can be obtained from the optical properties of dust with an uncertainty of 20-30% (Ansmann et al., 2012; Mamouri and Ansmann, 2014)."

Page 10, lines 12-14: The information included here should be provided earlier in the section, before discussing the results.

[REPLY] The information regarding the Clim-DE and Con-DE products is provided in section 2.3. Here, we repeat the difference between the products in order to introduce the next paragraph, which is devoted to the Con product description. We rephrased the sentence to be clearer:

Page 13, line 28: "The decreasing intensity with height and latitude found in the Clim-DE product is representative of the average dust distribution over the area. However, this behaviour is not representative of the distribution during dust episodes over Europe. This is because the extinction coefficient values presented in Fig. 4 for the Clim-DE product are produced by averaging partially and fully dominated dust cases. In order to describe the spatial patterns and the intensity of the dust plumes during episodes only, we introduce and discuss the Con-DE product in the next section."

Page 10, line 23: Replace "populations of dust" by "dust features"

[REPLY] It is replaced.

Page 10, line 25: Indicate the other seasons and regions where the two distinct layers are observed

[REPLY] We deleted this part of the paper.

Page 11, lines 3-12: This paragraph should be moved to later on in the manuscript, in order to keep all the discussion related to figure 4 together. Additionally, more discussion on depolarization should be provided here.

[REPLY] We deleted this part of the manuscript.

Page 11, line 16: Replace "in the same range with" by "in the same range as"

[REPLY] It is replaced.

Page 11, line 32: At the end of section 3.3 you mentioned that Con-De will be used to discuss if the decreasing intensity with height and latitude is representative, but this is not discussed in section 3.4. Please, include some sentences. Additionally, some more discussion comparing the results from sections 3.4 and 3.3 will be interesting.

[REPLY] The paragraph at the end of 3.3 has been changed to highlight the difference between the two products, and to justify the need of discussing both.

Regarding the comparison of the two products presented in 3.3 and 3.4, we have included a comment in the first paragraph:

Page 14, line 7: "This is because the two products differ mostly over areas which are not dominated by dust." There is no meaning to our opinion to elaborate further on this comparison, since the difference between the two products has to do with the frequency of occurrence of dust in relation to other aerosol types. Although we introduce a new Table 3 in the end of Sect. 3.4 so as the readers can have a quantitative representation of the two products. The new part is:

Page 15, line 10: "A quantitative representation of the Clim-DE and Con-DE products is provided in Table 3. In this, regional statistics on the two products, along with their standard deviation are provided for three altitudinal ranges (0 – 2, 2 – 4 and 4 – 6 km a.s.l.)."

Table 3: Regional statistics on the dust extinction coefficient for altitudes between 0 to 2km, 2 to 4 km and 4 to 6 km (a. s. l.).

	0 – 2 km	**2 – 4 km**	**4 – 6 km**	
	Clim-DE / Cond-DE / St. dev	**Clim-DE / Cond-DE / St. dev**	**Clim-DE / Cond-DE / St. dev**	**Domain**
NE Africa				[10E,30E] [20N,30N]
JFM	42 / 50 / 74 Mm^{-1}	7 / 43 / 20 Mm^{-1}	0 / 25 / 5 Mm^{-1}	
AMJ	66 / 66 / 88	44 / 53 / 48	18 / 48 / 26	
JAS	42 / 42 / 64	30 / 40 / 37	13 / 43 / 22	
OND	34 / 34 / 51	17 / 32 / 24	3 / 27 / 9	
NW Africa				[10W,10E] [20N,35N]
JFM	46 / 60 / 80 Mm^{-1}	6 / 45 / 18 Mm^{-1}	0 / 29 / 5 Mm^{-1}	
AMJ	73 / 73 / 90	41 / 59 / 49	13 / 51 / 25	
JAS	113 / 113 / 131	83 / 83 / 71	43 / 50 / 40	
OND	59 / 59 / 86	35 / 48 / 43	10 / 36 / 19	
C-E Med.				[10E,30E] [30N,45N]
JFM	22 / 44 / 55 Mm^{-1}	4 / 48 / 16 Mm^{-1}	0 / 31 / 5 Mm^{-1}	
AMJ	27 / 35 / 54	17 / 52 / 34	5 / 42 / 15	
JAS	18 / 18 / 28	13 / 33 / 22	4 / 37 / 12	
OND	19 / 23 / 32	10 / 35 / 19	2 / 27 / 7	
C-W Med.				[10W,10E] [35N,45N]
JFM	5 / 24 / 33 Mm^{-1}	1 / 32 / 7 Mm^{-1}	0 / 21 / 2 Mm^{-1}	
AMJ	10 / 23 / 38	6 / 35 / 19	1 / 31 / 8	
JAS	16 / 22 / 40	13 / 33 / 23	5 / 38 / 14	
OND	10 / 22 / 33	4 / 29 / 14	0 / 29 / 4	
NE Europe				[10E,30E] [45N,60N]
JFM	4 / 37 / 41 Mm^{-1}	0 / 29 / 5 Mm^{-1}	0 / 15 / 1 Mm^{-1}	
AMJ	8 / 17 / 27	2 / 21 / 17	0 / 14 / 2	
JAS	7 / 14 / 21	2 / 16 / 9	0 / 16 / 2	
OND	4 / 16 / 19	1 / 21 / 6	0 / 14 / 1	
NW Europe				[10W,10E] [45N,60N]
JFM	1 / 16 / 16 Mm^{-1}	0 / 16 / 2 Mm^{-1}	0 / 15 / 1 Mm^{-1}	
AMJ	4 / 16 / 16	1 / 21 / 11	0 / 14 / 2	
JAS	3 / 15 / 15	1 / 22 / 7	0 / 18 / 2	
OND	2 / 16 / 15	0 / 23 / 4	0 / 13 / 0	

Page 12, line 18: Replace "statistical significant" by "statistically significant"

[REPLY] It is replaced.

Anonymous Referee #3

In this manuscript, "3D evolution of Saharan dust transport towards Europe based on a 9-year EARLINET-optimized CALIPSO dataset", the authors use a combination of CALIPSO and EARLINET to present a climatology of recent dust vertical distribution and transport to Europe from Africa. The consideration of both climatological extinction and 'conditional' extinction is useful to elucidate the episodic transport as well as the dust distribution.

The manuscript is generally well written and the climatology will be useful to the community and to evaluate models. However, there is a lack of discussion of uncertainties in the product and some limited interpretation of the particle depolarization ratio and interannual variability that need revision. Please see the major and minor comments below.

[REPLY] We thank the reviewer for the thorough revision and comments. We agree with the importance of the discussion on the uncertainties in the product, thus we added a new section (Section 2.4) discussing all the uncertainties of the product in the manuscript. We decided to delete the particle depolarization ratio discussion from the paper, so as to help the reader concentrate on the other parts of this work. The section of the interannual variability is substantially revised. Replies to general and specific comments can be found below.

Major Comments

There is limited discussion of the uncertainties and detection limits of dust occurrences throughout the manuscript. There are some very high occurrences of dust shown in regions far from dust sources in Figure 1 (e.g. the North Atlantic). How certain are we that this is actually dust and based on what detection limit? Similarly, Figures 3 and 4 show infrequent but high extinction dust at the surface at high latitudes. Can we besure this is not a retrieval artifact? When climatological extinctions as low as 5 Mm-1 are considered (e.g. pg9 line 22) it would be useful to know the uncertainty on the estimates.

[REPLY] We thank the reviewer for these comments. We added a new section (Section 2.4) discussing the uncertainties of the produced product. In the same section, we mention also the detection limit for dust occurrences and the uncertainty introduced from this choice by stating: "Moreover, we have calculated that the uncertainty of the dust occurrences presented in Sec. 3.1 ("% Dust / Used Overpasses"), might be up to 8% in latitudes away from the sources, induced from the error in the selection of the δ_{nd} value (0.03±0.04)." In a more detail explanation on how this percentage is estimated: the selected detection limit is based on depolarization measurements, and any layer with depolarization values greater than 0.03 is considered as mixture of dust with other aerosols. This detection threshold correspond to the lowest the depolarization values found in nature for clean marine, smoke and anthropogenic aerosols, i.e., 0.03 ± 0.01, 0.06 ± 0.01 and 0.06 ± 0.01, respectively. We estimated the uncertainty that this detection limit may induce in the occurrences of dust far from sources. For cases where the depolarization of the non-dust feature is$0.03 < \delta_{\mathrm{nd}} \leq 0.075$, the low selected δ_{nd} value, may introduce error as high as 100%. In CALIPSO dataset of our domain, these cases correspond to less than 4% of the dust and polluted dust layers used (1% of the dust layers used and 8% of the polluted dust layers used). This uncertainty is transferred to the uncertainty of the dust occurrences presented in Sec. 3.1, inducing a positive bias up to 8% in latitudes away from the sources for the parameter “% Dust / Used Overpasses”, as this parameter refers to observations with DOD > 0.

In Figures 3 and 4 (new figures 4 and 5), the uncertainty of the dust extinction values close to the surface and at high latitudes are <54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values in these figures is <20%. Nevertheless, the standard deviation of the Cilm-DE product, originating from the natural variability of the dust events, may excess to a large extent the uncertainty of the retrieval, reaching values from 100% to 200%.

The following section is added in the manuscript (page 7, line 31):

“2.4 Dust product uncertainties

The sources of uncertainties for the pure-dust product are discussed in this section. CALIOP is able to detect aerosol layers with $AOD > 0.005$ and $\beta > 0.25\ Mm^{-1}\ sr^{-1}$ (Winker et al. 2009). The uncertainty estimation of particulate backscatter, extinction and AOD retrievals reported in the CALIPSO Level 2, Version 3 Data Release, are based on the simplified assumption that all the uncertainties are random, uncorrelated and produced no biases (Young, 2010). More specifically, ignoring multiple scattering, the errors in the layer optical depth calculations typically arise from three main sources: (a) signal-to-noise ratio within a layer, (b) calibration accuracy, and (c) the accuracy of the lidar ratio used for the extinction retrieval. The lidar ratio uncertainty is the dominant contributor to the total uncertainties, and the relative error in the layer optical depth is always at least as large as the relative error in the lidar ratio of the layer, and grows as the solution propagates through the layer (CALIPSO L2-V3, 2010). In our dataset the typical uncertainties in the CALIPSO Level 2 version 3 product are between 30% and 100% for the AOD, between 30% and 160% for the aerosol backscatter and extinction coefficient and >100% for the particle depolarization ratio.

Several studies report that CALIPSO underestimates the columnar AOD due to undetected aerosol in the free atmosphere. For instance, Rogers et al. (2014) report a ~ 0.02 AOD CALIPSO underestimation, when compared to collocated airborne HSRL measurements over the North American and Caribbean regions at night. In their data, the dust layers were primarily non-opaque with extinction less than $1\ km^{-1}$ so there were negligible multiple scattering effects. The aforementioned detection limits and uncertainties of CALIPSO products are propagated to the dust product presented here.

As already described, the EARLINET-optimized CALIPSO dust product is derived using the depolarization-based separation method, coupled with the selection of a uniform climatological LR value. These steps introduce uncertainties in the pure dust product. In particular, the uncertainty in the selection of the representative LR (55 ± 11) is 20% for the study area (e.g. Wandinger et al. 2010; Baars et al. 2016 and references within). This uncertainty in LR is less than half of the uncertainty of the generic LR in CALIPSO version 3 product (40 ± 20 for dust layers and 55 ± 22 for polluted dust layers). As already addressed in several studies (e.g. Wandinger et al. 2010; Schuster et al. 2012; Amiridis et al. 2013), CALIPSO V3 dust extinction coefficient and AOD values are about 30% lower than those obtained from collocated ground-based Raman lidar retrievals due to the low LR used in the CALIPSO aerosol retrievals. Amiridis et al. (2013) applied the EARLINET LR for the pure dust CALIPSO cases above North Africa and Europe, and compared with synchronous and collocated AERONET measurements. The results showed an absolute bias on the AOD of the order of −0.03, improving on the statistically significant biases of the order of −0.10 reported in the literature for the original CALIPSO product. The bias of -0.03 is similar to the low bias of CALIPSO's column AOD due to undetected aerosol layers. In Kim et al. (2017), they found a global mean undetected layer AOD of 0.0031 ± 0.052 by comparing 2 year of CALIPSO (L1-V4) and MODIS AODs.

Regarding the error induced from the application of the dust separation method, this might be due to the selection of the particle depolarization ratio of dust and the other aerosol types (marine, anthropogenic or smoke). Tesche et al. (2009; 2011) and Ansmann et al. (2012) estimated that the uncertainty in dust related backscatter coefficients is 15-20% in well-detected dessert dust layers and 20-30% in less pronounce aerosol layers. Moreover, we have calculated that the uncertainty of the dust occurrences presented in Sec. 3.1 ("% Dust / Used Overpasses"), might be up to 8% in latitudes away from the sources, induced from the error in the selection of the δ_{nd} value (0.03±0.04). Finally, an uncertainty induced in the dust product presented in this work, originates from the CALIPSO subtype selection algorithm. In this version of our product, both dust and polluted dust observations are considered polluted dust, and the pure dust component is separated using the dust separation method. The other aerosol layers, which are characterised as clean marine (CM), smoke (S), polluted continental (PC) or clean continental (CC) are considered to be cases clear of dust and are not tested for a dust component. This introduces negligible error in our analysis and is expected to induce a negative bias in the parameter "% Dust / Used Overpasses" less than 8%, mainly in areas above sea. In general, Clim-DE and Cond-DE products, the uncertainty of the dust extinction values close to the surface and at high latitudes is < 54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values is < 20%. Nevertheless, the standard deviation of the climatological products, coming from the natural variability of the dust events, may exceed to a large extent the uncertainty of the retrieval, reaching values as high as 100% and 200%.

In the latest release of CALIPSO Level 2 version 4 product (CALIPSO L2-V4, 2016), based on CALIPSO team announcement, the accuracy of the original CALIPSO product is increased and the uncertainty is reduced. This version is based on a revised calibration approach which leads to an increase in the total attenuated backscatter coefficients by ~3% overall as compared to the version 3 values (CALIPSO L1-V4, 2016). Several bugs are fixed and a major overhaul of the aerosol subtyping algorithms along with revisions on the lidar ratio selections is applied."

The retrieval is provided only for clear-sky conditions. Can you comment on how this might bias the dust extinction and how it relates to cloud formation (mentioned on page 10)?

[REPLY] We thank the reviewer for this comment. Indeed the restrictions of the dataset, related to the cloudy meteorological conditions were not addressed in the manuscript, therefore we commented analogously below.

First, let us address the second part of the question, to comment on how it relates to cloud formation (mention on page 10). The impact of dust on cloud formation is part of a second study we are working on. In this work, we use dust profiles from CALIPSO, in combination with EARLINET parameterizations, in order to calculate the dust mass concentration for particles with radius greater than 250 nm and from there, based on known ice nuclei parameterizations to estimate ice nuclei concentration profiles. A detailed analysis of this technique is provided in the work of Mamouri and Ansmann (2016). In order not to confuse the readers, we decided to delete the part where we mention "and the impact on cloud formation" from our manuscript.

Regarding the first part of the reviewer's comment, we added a new Table in the manuscript, in order to provide a more informative representation of the dataset. In this table (Table 3) the percentages of the cloud free observations used, in relation to the total observations are provided, aggregated on 6 areas over the study region. Furthermore we added the following discussion in the manuscript (page 9, line 14):

"Table 2 shows the impact of cloud contamination in our dataset. During AMJ, JAS and OND, more than 80% of the total observations are cloud-free above North Africa. Above Central-East Mediterranean (C-E Med.), more than 80% of the total observations are cloud-free and above Central West Mediterranean (C-W Med.) approximately 60% - 80% of the total observations are cloud-free. With increasing latitude, the cloud-free sampling is reduced to percentages of ~ 40% - 60% in latitudes greater than 45° N. During JFM, cloudy conditions restrict our dataset in the greatest extent. During the same period, the cloud-free cases used represent ~ 80% of the total observations above North Africa, approximately 60 - 70% of the total observations above the Mediterranean and ~ 30% in the domain between 45° N - 60° N. In the areas (and seasons) where clouds do not dominate (e.g. 70% clear-sky conditions), our cloud-free product is considered representative of the dust distribution. In areas where cloudy skies dominate (e.g. 30% clear-sky conditions), the clear-sky CALIPSO profiles cannot be considered as representative of all meteorological conditions, so the results should be used with caution."

In Figure 1 there is a strong boundary along the European coastline for dust occurrences, is this the result of a marked difference in used overpasses between the mainland and the Mediterranean? Please make sure that this feature is explained.

[REPLY] Unfortunately, we cannot see the boundary the reviewer is referring to along the European coastlines. There might be a boundary along the French coastlines, however it looks like that over the Iberian Peninsula, Greece and Italy the number of dust overpasses well penetrate over land.

I don't think simply listing papers that have used specific instruments to explore dust over the Mediterranean is the best way of presenting the introduction (pg3 lines 10-20). Please consider reconstructing this paragraph to briefly discuss what these papers show that is relevant to understanding dust transport to Europe, rather than framing around the instrument used.

[REPLY] We reconstructed this paragraph according to the reviewer's suggestions. The new paragraph is (page 3, line 8):

“Many studies have used satellite observations to derive dust properties over the Mediterranean during the last 15 years. Most of them focus on the horizontal distribution of dust using passive remote sensing techniques. Antoine and Nobileau, (2006) used SeaWIFS (Sea-Viewing Wide Field-of-View Sensor) observations to study the seasonal evolution and variability of dust aerosols over the broader Mediterranean Sea during the period 1998-2004. Alpert and Ganor (2001) and Israelevich et al. (2002) used the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) product in order to study the concentration of dust over Middle East and the dust sources of Northern Africa, respectively. The MODIS instrument, onboard both Terra and Aqua satellites has been extensively used in studies of airborne mineral dust over the Mediterranean basin. Barnaba and Gobbi (2004) analysed one-year (2001) MODIS/Terra AOD at 550 nm observations and reported on the spatial distribution and seasonal variability of aerosols, including dust, over the Southern Europe, with a focus over the Mediterranean region. Papayannis et al. (2005) used MODIS/Terra data synergistically with lidar measurements and dust model simulations and investigated the vertical distribution of aerosols during dust outbreaks over Greece. Kosmopoulos et al. (2008) and Papadimas et al. (2008) used MODIS/Terra and MODIS/Aqua to investigate the seasonal and interannual variability of AOD at 550 nm over Athens (Greece) and over the broader Mediterranean Sea, respectively. Marey et al. (2011) analysed ten-years of MODIS data synergistically with MISR and OMI and they produced a monthly climatology of aerosols over a domain covering the Nile Delta and northeast Africa.”

The seasonal climatological and conditional meridional dust extinction product will be useful for evaluating model representation of dust transport to Europe. I recommend that the authors make this available to the research community and include a link to the dataset in the manuscript, if possible.

[REPLY] We added a new section for data availability where we provide the availability of this dataset. In the new Section 5 we provide this information (page 17, line 22) :

“The LIVAS database is publicly available at http://lidar.space.noa.gr:8080/livas/. LIVAS EARLINET-optimized pure dust products are available upon request from Eleni Marinou (elmarinou@noa.gr) and Vasilis Amiridis (vamoir@noa.gr).”

The section on interannual variability is quite weak. The comparisons with other studies should be relevant to the time period considered in this work.

[REPLY] We agree with the reviewer that a more extended discussion on the interannual variability section would improve the structure of the manuscript. The referenced literature was mainly focused on studies related to the decrease of both dust concentration and frequency close to the surface, for two basic reasons. Firstly, most of the available studies focus on the interannual variability and trends of AOD, not of DOD. This is due to the difficulty of disentangling the dust component of the total aerosol load. Secondly, interannual variability studies have been carried out mainly over the second half of the past decade and mostly by using columnar SeaWiFS, MODIS (Aqua/Terra), MISR, AVHRR and AERONET data. In this study, CALIIOP/CALIPSO vertically-resolved observations in nine years are used, which provide an accurate and robust way of identifying mineral dust from space. Furthermore, the methodology has been established and validated based on EARLINET for CALIPSO mineral dust research. In this way, CALIPSO is considered as an ideal tool from space to decouple the dust component from the total aerosol burden and for studies of the variability of DOD. Nevertheless, since the authors agree with the reviewer and in order to ratify the results, modifications on the manuscript were made. The authors extended the list of referenced studies related to the interannual variability not only for DOD but additionally for AOD, with an effort to be more focused over the study region. The "Interannual variability of dust" section is modified by adding the following text (page 15, line 29):

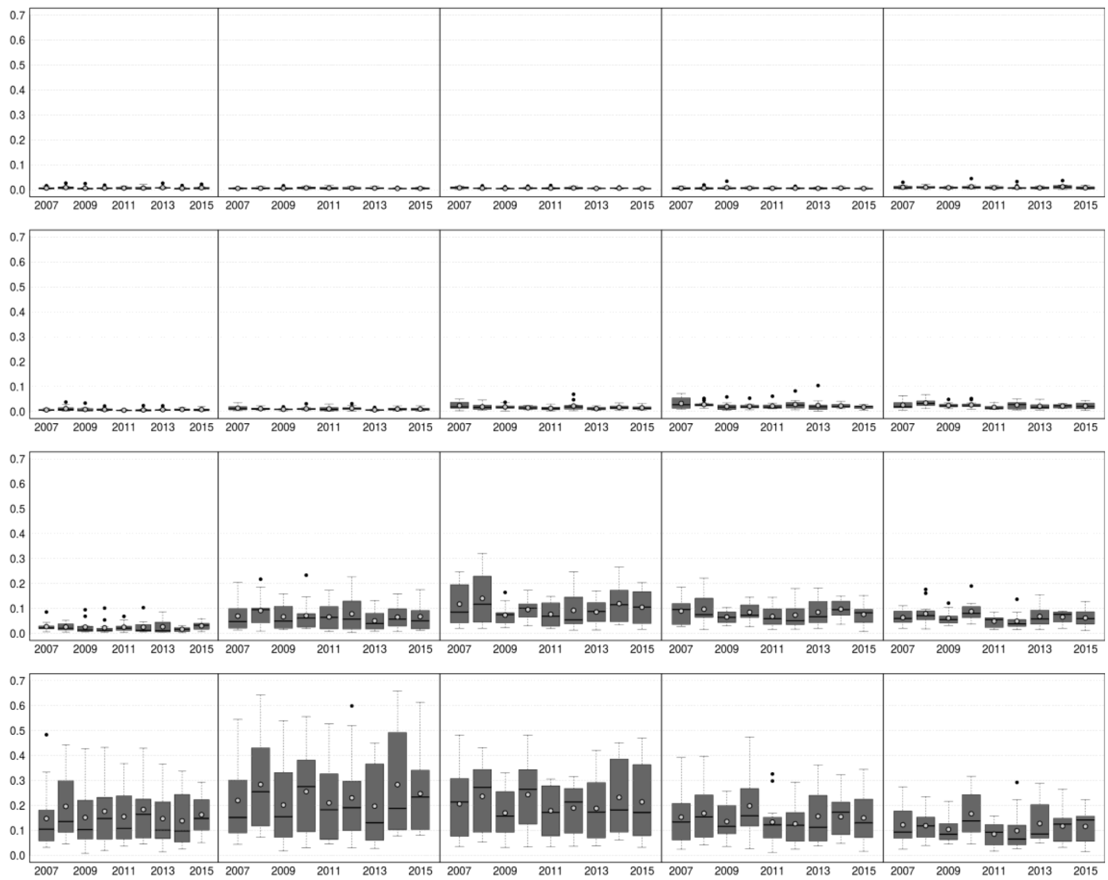
"In comparison with studies relevant to the time period considered in this work, the DOD decrease of 0.001 yr^{-1} over the northern coast of Africa is in agreement with Floutsi et al. (2016), who based on 12 years of MODIS-Aqua observations (2002-2014) reported an average decrease of 0.003 yr^{-1} for the coarse mode fraction of AOD over the broader Mediterranean Sea. Furthermore, over the same domain the decreasing trend of DOD coincides with the decrease of Saharan desert dust episodes as reported by Gkikas et al. (2013). Regarding the AERONET stations over the domain of northern Africa and Europe, Yoon et al. (2012) reported on the trends of AOD at 440 nm along with the corresponding Ångström Exponents (440 and 870nm). The documented negative trends over the AERONET stations of Avignon (France), Dakar (Senegal) and Ispra (Italy) are in agreement with the negative DOD reported here, although with discrepancies in the magnitude, while trend disagreements are observed over the AERONET station of Banizoumbou (Niger). The decreasing trends of DOD observed over the domain northern of Africa and Europe coincide with the generally documented downward AOD trends reported based on several satellite observations of MODIS/Aqua, MODIS/Terra, MISR and SeaWiFS (Pozzer et al., 2015; de Meij et al., 2012; Hsu et al., 2012; Georgoulias et al. 2016b). More particular, in the most recent study of Georgoulias et al. (2016b), using MODIS/Terra and MODIS/Agua observations, they reported negative statistically significant trends over Algeria, Egypt and the Mediterranean and positive trends over Middle East. Overall, for the Mediterranean they reported an AOD trend of -0.0008 yr^{-1} for the MODIS/Terra observations (2000 – 2015) and -0.0020 $yr^{-1}$for the MODIS/Aqua observations (2002 – 2015), with the trends being statistical significant at the 95% confidence level in both cases."

There does seem to be a general downward trend, but based on the lack of significance in many regions it is understandably difficult to determine long term trends over a relatively short 8 year period. Maybe the authors could include a timeseries panel in Figure 6 to indicate the interannual variability, rather than focus on the weak trends?

[REPLY] In our study, we calculate the DOD trend along with the statistical significance of each trend for the period 2007-2015 (108 monthly values). We also believe that trends might change if a longer time scale is used. According to the reviewer's suggestion, we added a timeseries panel as Figure 7, including the interannual variability of the 9 year observations based on monthly mean DODs. The interannual section was modified, and the following text is added (page 16, line 13):

"In our study, we calculate the DOD trend along with the statistically significance of each trend for the period 2007-2015 (108 monthly values). Nine years are considered a small period for a robust trend calculation and it would be interesting to repeat the same analysis in the future to extended aerosol record. The de-seasonalization process as well as the trend are describing the examined period only. Figure 7 shows the DOD internal variability of the 20 individual areas, as it is calculated from monthly mean DODs. Is evident from this figure that the DOD values in 2008 are relatively higher than the other years and in almost all the domains bellow 40°N. Similarly, relatively high values are observed in some of these areas for the year 2010. Since these years are at the beginning of our study period, they have a significant contribution on the negative trends observed during the examined period."

Figure 7: Interannual variability of the DODs for the 10° x 10° grid cells depicted in Fig. 6, for the period 2007-2015.



Minor Comments

Please replace all instances of 'utilize' with 'use'

[REPLY] It is replaced throughout the manuscript

pg1 ln21 - "During spring..." sentence is not clear, please revise.

[REPLY] We revised the sentence as (page 1, line 21): "During spring, the spatial distribution of dust shows a uniform pattern over the Sahara desert."

pg1 ln22 - "on" should be "in"

[REPLY] It is replaced.

pg1 ln23 - "0.1", should this be "up to 0.1"?

[REPLY] It is rephrased: **"**The dust transport over the Mediterranean Sea results in mean Dust Optical Depth (DOD) values up to 0.1."

pg1 ln28 - units are sometimes italicized, other times not

[REPLY] We harmonized the units format in the manuscript, and, now, they are italicized everywhere.

pg1 ln31 - change to "the Alps and Carpathian Mountains"

[REPLY] It is changed.

pg2 ln25 - remove "now"

[REPLY] It is removed.

pg3 ln30 - what is meant by "large scale statistics"

[REPLY] This phrase is removed and replaced by the phrase (page 4, line 4):

"To our knowledge, this is the first time that a 3D pure-dust dataset is statistically analyzed over the area of North Africa and Europe in order to provide not only the horizontal but also the vertical patterns of Saharan dust intrusion in the Mediterranean."

pg4 ln22 - extra space after "biases"

[REPLY] It is removed.

pg5 ln13 - perhaps provide the link as a reference?

[REPLY] We provide the link as a reference now. In the discussion (page 5, line 20):

"In brief, CALIPSO L3 version 3 screening procedure is followed (Winker et al., 2013; CALIPSO L3-V3, 2015)"

Reference:

CALIPSO L3-V3: CALIPSO: Data User's Guide - Data Quality Statement - Lidar Level 3 Aerosol Profile Monthly Product Version 3.00, link: http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/data_summaries/l3/CALIOP_L3Products_3-00_v01.php, 2015.

pg5 ln21 - "categorized"

[REPLY] It is removed.

pg6 ln17 - "However..." it is not clear why this is an issue. Please elaborate or remove.

[REPLY] We removed the sentences from the text.

pg7 ln8 - "suppressed", this should be caveated as there are still significant emissions from African regions, like the Bodele, that are just not transported northwards.

[REPLY] We thank the reviewer for this comment. Indeed the sentence was generic, and hence not correct. We specify it accordingly (page 9, line 25):

"During autumn and winter the emission and transport of dust towards Europe is suppressed due to the more effective removal processes and due to the atmospheric dynamics favouring the transport of dust towards the Atlantic (e.g. Israelevich et al., 2002; Schepanski et al., 2009)."

pg7 ln23 - "Strong topographical heights", unclear meaning - please rephrase

[REPLY] We deleted this part, as it was unclear. Now the sentence is (page 10, line 8):

"The activated dust sources are located in the broad "dust belt" and are usually associated with topographical lows in the arid regions and with the intermountain basins (Prospero et al., 2002)."

pg8 ln3-5 - It is not clear what this tells us (high DOD, high sdev). Please explain what this indicates.

[REPLY] Standard deviation is an indication of the variability of the dataset. We deleted this part, as it was unclear.

pg8 ln3 - "In general,"

[REPLY] Done.

pg8 ln31 - "situation", please be more specific.

[REPLY] We changed the sentence 9Page 11, line 27):

"During OND the horizontal pattern is similar to JJA however with much lower heights (Figs. 3g, h)."

pg9 ln11 - "England" should be "Ireland"

[REPLY] It is corrected.

pg9 ln15 - "England" should be "British Isles"

[REPLY] It is corrected.

pg10 ln2 - "higher" than what?

[REPLY] We rephrased that paragraph. Now the new sentence is (page 13, line 12):

"The values of Clim-DE are higher (>45 Mm^{-1}) over Africa during winter and spring, in relation with the ones observed during the other two seasons (<45 Mm^{-1}) and reach high altitudes (5-6 km a.s.l.) during spring and summer."

pg10 ln18 - no new paragraph and replace "Nevertheless" with "However"

[REPLY] Done.

pg10 ln23 - delete the first sentence

[REPLY] We deleted it.

pg10 ln24 - "Number of Exceedances", exceedances of what? Perhaps "Number of occurences" or "Number of observations" makes more sense?

[REPLY] We changed the "Number of Exceedances (NoE)" into “Number of dust observations (dO)” according to the suggestion of the reviewer.

pg11 ln3 - "move" should be "moves"

[REPLY] It is changed.

pg11 ln11 - "mean" should be "means"

[REPLY] It is changed.

pg11 ln11-20 - this section is out of place as the following paragraph returns to Fig.4. Also, sentences in the paragraph somewhat contradict each other. If the PDR is a means of estimating age, but "cannot be considered as a possible age index". If the latter is true, why is this useful? The paragraph needs moving and restructuring, or removing (which would also mean removing the figure) unless the PDR provides some insight.

[REPLY] In the figure, were we presented the particle depolarization ratio for the cases used for the production of Cond-DE, it was evident that the depolarization is higher for air masses closer to the desert while it decreases as the air-masses travel towards Europe. This is due to the mixing of dust with other aerosol particles, which takes place after some days of transport. However, the depolarization ratio cannot be considered as a possible age index of the pure-dust particles, since it only provides the mixing of dust with other particles (Tesche et al., 2009). It was used here as an age estimator only because the Sahara desert is away from Europe and the mixing of transported dust with anthropogenic particles occurs as soon as the plumes mix with anthropogenic particles over the European Continent.

Because the revised manuscript, after the suggestion of the reviewers, has two new figures and two new tables, which highlight in our opinion very interesting and informative aspects of the product, we decided to delete the depolarization part (and plot) from the paper, so as to help the reader concentrate on the other parts of this work.

pg11 ln22 - I think panel "l" should be panel "i"

[REPLY] It is corrected.

pg11 ln25 - "plums" should be "plumes"

[REPLY] It is corrected throuout the manuscript.

pg11 ln26 - give the latitude range of the mountainous regions

[REPLY] We elaborated the sentence by including the range of the mountainous regions (page 14, line 26):

"The trapping of Saharan dust from the mountainous ridges of Europe (located between 40°N – 50 °N, e.g. the Alps 45°N-48°N) is also evident by the Con-DE cross-sections(e.g. Fig. 5i, m).

pg11 ln29 - "dust in" should be "dust at"

[REPLY] It is changed

pg11 ln30 - can you be more specific why the deposition is stronger during that season - is it primarily wet or dry deposition?

[REPLY] We changed the sentence as (page 14, line 29):

"Dry deposition of dust at these areas result also in the formation of "brown snow" and albedo reduction, with profound climatological implications (e.g., Fujita, 2007; Shahgedanova et al., 2013). This phenomenon is more intense during JFM period due to the advection of dust at lower heights."

pg11 ln31-34 - why is there a sudden drop off in extinction at 40N during the AMJ season? Please explain this.

[REPLY] We addressed this issue by adding the sentence (figure 14, line 32):

"The transport of dust during AMJ is mostly due to the eastward propagation of N.Africa – Mediterranean low pressure systems (Sharav cyclones). Dust is embedded in the cyclonic circulation and the penetration to latitudes higher than 40°N is limited."

pg12 ln1 - I think panel "i" should be panel "l"

[REPLY] It is corrected.

pg12 ln19-24 - the studies referenced consider longer time periods and/or different geographical regions, please alter to so that the discussion relates better to the region and period you are considering.

[REPLY] As mentioned already in the similar major comment, the "Interannual variability of dust" section is modified by adding the following text (page 15, line 29):

"In comparison with studies relevant to the time period considered in this work, the DOD decrease of 0.001 yr^{-1} over the northern coast of Africa is in agreement with Floutsi et al. (2016), who based on 12 years of MODIS-Aqua observations (2002-2014) reported an average decrease of 0.003 yr^{-1} for the coarse mode fraction of AOD over the broader Mediterranean Sea. Furthermore, over the same domain the decreasing trend of DOD coincides with the decrease of Saharan desert dust episodes as reported by Gkikas et al. (2013). Regarding the AERONET stations over the domain of northern Africa and Europe, Yoon et al. (2012) reported on the trends of AOD at 440 nm along with the corresponding Ångström Exponents (440 and

870nm). The documented negative trends over the AERONET stations of Avignon (France), Dakar (Senegal) and Ispra (Italy) are in agreement with the negative DOD reported here, although with discrepancies in the magnitude, while trend disagreements are observed over the AERONET station of Banizoumbou (Niger). The decreasing trends of DOD observed over the domain northern of Africa and Europe coincide with the generally documented downward AOD trends reported based on several satellite observations of MODIS/Aqua, MODIS/Terra, MISR and SeaWiFS (Pozzer et al., 2015; de Meij et al., 2012; Hsu et al., 2012; Georgoulias et al. 2016b). More particular, in the most recent study of Georgoulias et al. (2016b), using MODIS/Terra and MODIS/Agua observations, they reported negative statistically significant trends over Algeria, Egypt and the Mediterranean and positive trends over Middle East. Overall, for the Mediterranean they reported an AOD trend of -0.0008 yr^{-1} for the MODIS/Terra observations (2000 – 2015) and -0.0020 $yr^{-1}$for the MODIS/Aqua observations (2002 – 2015), with the trends being statistical significant at the 95% confidence level in both cases."

pg12 ln26 - replace LR with lidar ratio

[REPLY] It is replaced.

pg24 - The EARLINET reference is repeated multiple times.

[REPLY] The different EARLINET references refer in different EARLINET publications / products. In particular: (1) EARLINET all observations (2000–2010), 2014a, (2) EARLINET climatology (2000–2010), 2014b, (3) EARLINET correlative observations for CALIPSO (2006–2010), 2014c, (4) EARLINET observations related to volcanic eruptions (2000–2010), 2014d, (5) EARLINET observations related to Saharan Dust events (2000–2010), 2014d.

Figure 2(b,d,f,h) - Why is the color bar different for the CoM panels relative to the Top Height panels when they are both showing altitude? Consider using the same color to avoid confusion

[REPLY] We used different range for the altitude in the two plots, because the CoM variation of the area is not nicely depicted when using the same color bar with Top Height. We understand that this might bring confusion to the readers, so we changed the figures using the same color bar and ranges.

Figure 2 - In titles, "TOP" should be "Top"

[REPLY] It is changed.

Figures 3,4,5 - longitude and latitude labels are too small on the domain panels

[REPLY] The labels size is increased and it is more visible in the new version of the manuscript.

Anonymous Referee #4

General remarks:

The present manuscript provides a monthly climatology (from 2007 to 2015) of African dust based on an optimised CALIPSO dust product was recently developed with a regional correction of the Saharan dust LR using EARLINET measurements (Amiridis et al., 2013). The monthly climatology of African dust obtained allows the description of the spatiotemporal features of dust properties over North Africa and Europe. The study of the mean state climatology shows strong seasonal shifts in dust source regions and transportation pathways. While the results of the study are interesting to be published, their presentation and discussion are not yet sufficient to be published in Atmospheric Chemistry and Physics in the current form. Therefore, it is worth to be published after addressing major revisions which are explained below along with a few other details.

[REPLY] We thank the reviewer for the thorough revision and comments. Replies to the general and specific comments follow below.

Major comments:

In Amiridis et al. (2013), this EARLINET-optimized CALIPSO dust optical depth (for the period 2007-2011) is described and qualitatively compared with MODIS and AERONET. The present manuscript is focusing on the analysis of the resulting EARLINET-optimized CALIPSO dust climatology. I would be desirable to include a short discussion of the uncertainties of the EARLINET-optimized CALIPSO dust product. I understand that this discussion is partly in Amiridis et al. (2013, 2015) although the authors should include a summary in Sect. 2.2 as well as about the uncertainties of the algorithm of CALIOP to determine the corresponding aerosol subtype (in Sect 2.1).

[REPLY] We added a new section 3.5 discussing the uncertainties related to the EARLINET-optimized CALIPSO dust product. Moreover, we added a summary in Sect. 2.2 about the uncertainties of the algorithm of CALIOP to determine the corresponding aerosol subtype, referring to the evaluation done with NASA's HSRL and presented in Burton et al. (2013).

The summary, (page 4, line 24): "Burton et al. (2013) showed an 80% successful detection of dust from CALIPSO, upon comparison to underflights with the HSRL system of NASA. This score is considered very high for aerosol typing purposes and is attributed to the depolarization measurement capability of the CALIOP sensor."

The new section 3.5 added in the paper (page 6):

"2.4 Dust product uncertainties

The sources of uncertainties for the pure-dust product are discussed in this section. CALIOP is able to detect aerosol layers with $AOD > 0.005$ and $\beta > 0.25\ Mm^{-1}\ sr^{-1}$ (Winker et al. 2009). The uncertainty estimation of particulate backscatter, extinction and AOD retrievals reported in the CALIPSO Level 2, Version 3 Data Release, are based on the simplified assumption that all the uncertainties are random, uncorrelated and produced no biases

(Young, 2010). More specifically, ignoring multiple scattering, the errors in the layer optical depth calculations typically arise from three main sources: (a) signal-to-noise ratio within a layer, (b) calibration accuracy, and (c) the accuracy of the lidar ratio used for the extinction retrieval. The lidar ratio uncertainty is the dominant contributor to the total uncertainties, and the relative error in the layer optical depth is always at least as large as the relative error in the lidar ratio of the layer, and grows as the solution propagates through the layer (CALIPSO L2-V3, 2010). In our dataset the typical uncertainties in the CALIPSO Level 2 version 3 product are between 30% and 100% for the AOD, between 30% and 160% for the aerosol backscatter and extinction coefficient and >100% for the particle depolarization ratio.

Several studies report that CALIPSO underestimates the columnar AOD due to undetected aerosol in the free atmosphere. For instance, Rogers et al. (2014) report a ~ 0.02 AOD CALIPSO underestimation, when compared to collocated airborne HSRL measurements over the North American and Caribbean regions at night. In their data, the dust layers were primarily non-opaque with extinction less than $1\ km^{-1}$ so there were negligible multiple scattering effects. The aforementioned detection limits and uncertainties of CALIPSO products are propagated to the dust product presented here.

As already described, the EARLINET-optimized CALIPSO dust product is derived using the depolarization-based separation method, coupled with the selection of a uniform climatological LR value. These steps introduce uncertainties in the pure dust product. In particular, the uncertainty in the selection of the representative LR (55 ± 11) is 20% for the study area (e.g. Wandinger et al. 2010; Baars et al. 2016 and references within). This uncertainty in LR is less than half of the uncertainty of the generic LR in CALIPSO version 3 product (40 ± 20 for dust layers and 55 ± 22 for polluted dust layers). As already addressed in several studies (e.g. Wandinger et al. 2010; Schuster et al. 2012; Amiridis et al. 2013), CALIPSO V3 dust extinction coefficient and AOD values are about 30% lower than those obtained from collocated ground-based Raman lidar retrievals due to the low LR used in the CALIPSO aerosol retrievals. Amiridis et al. (2013) applied the EARLINET LR for the pure dust CALIPSO cases above North Africa and Europe, and compared with synchronous and collocated AERONET measurements. The results showed an absolute bias on the AOD of the order of −0.03, improving on the statistically significant biases of the order of −0.10 reported in the literature for the original CALIPSO product. The bias of -0.03 is similar to the low bias of CALIPSO's column AOD due to undetected aerosol layers. In Kim et al. (2017), they found a global mean undetected layer AOD of 0.0031 ± 0.052 by comparing 2 year of CALIPSO (L1-V4) and MODIS AODs.

Regarding the error induced from the application of the dust separation method, this might be due to the selection of the particle depolarization ratio of dust and the other aerosol types (marine, anthropogenic or smoke). Tesche et al. (2009; 2011) and Ansmann et al. (2012) estimated that the uncertainty in dust related backscatter coefficients is 15-20% in well-detected dessert dust layers and 20-30% in less pronounce aerosol layers. Moreover, we have calculated that the uncertainty of the dust occurrences presented in Sec. 3.1 ("% Dust / Used Overpasses"), might be up to 8% in latitudes away from the sources. Finally, an uncertainty induced in the dust product presented in this work, originates from the CALIPSO subtype selection algorithm. In this version of our product, both dust and polluted dust observations are considered polluted dust, and the pure dust component is separated using the dust separation method. The other aerosol layers, which are characterised as clean marine (CM), smoke (S), polluted continental (PC) or clean continental (CC) are considered to be cases clear of dust and are not tested for a dust component. This introduces negligible error in our analysis and is expected to induce a negative bias in the parameter "% Dust / Used Overpasses" less than 8%, mainly in areas above sea. In general, Clim-DE and Cond-DE products, the uncertainty of the dust extinction values close to the surface and at high latitudes is < 54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values is < 20%. Nevertheless, the standard deviation of the climatological products, coming from the natural variability of the dust events, may exceed to a large extent the uncertainty of the retrieval, reaching values as high as 100% and 200%.

In the latest release of CALIPSO Level 2 version 4 product (CALIPSO L2-V4, 2016), based on CALIPSO team announcement, the accuracy of the original CALIPSO product is increased and the uncertainty is reduced. This version is based on a revised calibration approach which leads to an increase in the total attenuated backscatter coefficients by ~3% overall as compared to the version 3 values (CALIPSO L1-V4, 2016). Several bugs are fixed and a major overhaul of the aerosol subtyping algorithms along with revisions on the lidar ratio selections is applied."

In Figure 1, there are some features that they look associated with the number of available observations, and consequently with the presence of clouds over the Mediterranean and Europe. I am not sure if the "%Dust/Used Overpasses" is enough to explain the DOD seasonal patterns in Europe. I would suggest to include an additional column with the number of used overpasses and to check how is working the algorithm of CALIOP to determine the corresponding aerosol subtype in this part of the domain.

[REPLY] The capability of CALIPSO to detect the dust subtype has been thoroughly evaluated by Burton et al., (2013) using a number of 109 underflights of CALIPSO with NASA's HSRL system and found that the detection of dust from CALIPSO is successful in 80% of the compared cases. Figure 1 is meant to present the frequency of CALIPSO dust occurences in the domain of our interest, in relation to the cloud-free overpasses of the sensor over the area. Following the helpful comment of the reviewer a new Table was added in the manuscript (Table 3), in order to provide a more informative representation of the dataset, including the percentages of the cloud free observations used, in relation to the total observations provided, aggregated on 6 areas over the study region. Furthermore we added the following discussion in the manuscript (Page 9, line 14):

Table 2 shows the impact of cloud contamination in our dataset. During AMJ, JAS and OND, more than 80% of the total observations are cloud-free above North Africa. Above Central-East Mediterranean (C-E Med.), more than 80% of the total observations are cloud-free and above Central West Mediterranean (C-W Med.) approximately 60% - 80% of the total observations are cloud-free. With increasing latitude, the cloud-free sampling is reduced to percentages of ~ 40% -60% in latitudes greater than 45° N. During JFM, cloudy conditions restrict our dataset in the greatest extent. During the same period, the cloud-free cases used represent ~ 80% of the total observations above North Africa, approximately 60 - 70% of the total observations above the Mediterranean and ~ 30% in the domain between 45° N - 60° N.

In the areas (and seasons) where clouds do not dominate (e.g. 70% clear-sky conditions), our cloud-free product is considered representative of the dust distribution. In areas where cloudy skies dominate (e.g. 30% clear-sky conditions), the clear-sky CALIPSO profiles cannot be considered as representative of all meteorological conditions, so the results should be used with caution."

In Page 10 Line 1, you mention that the results from Clim-DE can be used to estimate the impact of dust on cloud formation. As far as I understood, the EARLINEToptimized CALIPSO dust product is provided only for clear-sky conditions. In Sect. 4, you mention a recent paper from Mamouri and Ansmann (2016), but it is based on a ground-based lidar. Then, how could you estimate the dust impact on cloud formation from this EARLINET-optimized CALIPSO dust product?

[REPLY] The impact of dust on cloud formation is part of a second study we are working on. In this work, we use dust profiles from CALIPSO, in combination with EARLINET parameterizations, in order to calculate the dust mass concentration for particles with radius greater than 250nm and from there, based on known ice nuclei parameterizations to estimate ice nuclei concentration profiles. A detailed analysis of this technique is provided in the work of Mamouri and Ansmann (2016). An example of the application of this technique on collocated ground-based and CALIPSO data and comparison with in situ estimated ice nuclei will be presented in the upcoming ILRC Conference in Budapest. (Marinou, et al.: Lidar ice nuclei estimates and how they relate with airborne in-situ measurements, 28th ILRC, Bucharest, 25-30 July 2017). In order to keep the discussion as straightforward as possible, and to avoid confusing the readers, we decided to delete the corresponding part.

In my opinion, a further discussion about the similarities and discrepancies with other dust climatologies will enhance the impact of the results presented in the manuscript. Any comparison with other dust climatologies based on other datasets such as satellites (e.g. MODIS, AERONET, EARLINET or the official CALIPSO aerosol product); and models (as CAMS reanalysis or AEROCOM) is considered in the manuscript. Furthermore, how do the results of the present study improve those results of LIVAS (Amiridis et al., 2015)? These discussions will be useful for model evaluation, for example. Otherwise, it seems to me that some results are general and not enough justify in the manuscript.

[REPLY] We thank the reviewer for this comment. Amiridis et al., (2015), did not analyze the dust transport patterns. That paper describes the LIVAS database and focuses on the spectral conversion of the CALIPSO 532nm products for use in future ESA lidar missions that operate at 355nm. Following the suggestion of the reviewer, we calculated the optical depth using other available products such as the AOD from MODIS data and the DOD from MACC and RegCM4 models. We added a new figure, Figure 2, comparing our DOD seasonal maps with the ones produced with the above mentioned products, that is followed by a short discussion (page 10, line 26):

"In order to provide a more informative representation of the dust product presented here, we performed a comparison with MODIS AOD for the same period and the dust optical depth of the MACC reanalysis and a RegCM4 simulation for the period 2007-2012 and 2007-2014 respectively (Fig. 2). MODIS provides AOD for all natural and anthropogenic aerosol types. As a result the MODIS average value for the whole period and domain (0.267) is 281% almost three times, bigger than our product (0.095). It is noted thought that the values between the two satellite products are very similar over the Sahara desert. On the contrary, the corresponding average dust optical depth values of MACC (0.100) and RegCM4 simulations (0.104) reproduce better our product, since only dust is considered, though our product is lower by 5% and 8.6% respectively. Dust optical depth is overestimated over Europe and Mediterranean by MACC and RegCM4 simulations in comparison to our product in all seasons and especially in the hot periods AMJ and JJA, but the reasons of these discrepancies have to be further studied."

In Sect. 3.1 (Page 10) I don't understand the reason to include the dust mass concentration inversion results. This part of the discussion doesn't include any new insight with respect the analysis of the optical properties or any link to a particular previous study.

[REPLY] We removed the formulas and relevant discussion to the dust mass concentration inversion from the paper.

In Sect. 3.5, you could compare your results with a climatic index as the North Atlantic Oscillation Index (NAO) as Pey et at. (2013) did for PM10.

[REPLY] Following the analysis of Moulin et al. (1997) and Pey et al. (2013) we investigated the relation between NAO index and LIVAS AOD in seasonal and monthly basis (i.e., summer, winter, annually) for the period of our study but we did not find a statistically significant correlation and thus we did not include it in our results. Especially for summer the correlation between the NAO index and the LIVAS DOD over the western Mediterranean is negative but not statistically significant.

Is this de-seasonalised trend analysis sensitive to the number of available observations?

[REPLY] In our study, we calculate the DOD trend along with the statistical significance of each trend for the period 2007-2015 (108 monthly values). Nine years are considered a small period for a robust trend calculation and it would be interesting to repeat the same analysis in the future to an extended aerosol record. The de-seasonalization process as well as the trend are described only for the examined period only. In case we extend our analysis in the future by adding more years, results may change. We added this clarification in the manuscript (page 16, line 13):

"In our study, we calculate the DOD trend along with the statistically significance of each trend for the period 2007-2015 (108 monthly values). Nine years are considered a small period for a robust trend calculation and it would be interesting to repeat the same analysis in the future to extended aerosol record. The de-seasonalization process as well as the trend are describing the examined period only. Figure 7 shows the DOD internal variability of the 20 individual areas, as it is calculated from monthly mean DODs. Is evident from this figure that the DOD values in 2008 are relatively higher than the other years and in almost all the domains bellow 40°N. Similarly, relatively high values are observed in some of these areas for the year 2010. Since these years are at the beginning of our study period, they have a significant contribution on the negative trends observed during the examined period."

Minor comments:

Page 2 Line 13: Add Nickovic et al. (2016).

[REPLY] We added this reference.

Page 2 Line 16: Add Granados-Muñoz et al. (2016) and Bovchaliuk et al. (2016).

[REPLY] We added these references.

Page 3 Line 25: Replace Gkikas et al. (2015, ACPD) by Gkikas et al. (2016, ACP).

[REPLY] It is replaced.

Page 3 Line 30: When you said "large scale statistics of discriminate and optimized dust extinction and AOD fields from CALIPSO", what does it mean? What about Amiridis et al. (2013) and Amiridis et al. (2015)?

[REPLY] This phrase is removed and replaced by the phrase (page 4, line 4):

"To our knowledge, this is the first time that a 3D pure-dust dataset is statistically analysed over the area of North Africa and Europe in order to provide not only the horizontal but also the vertical patterns of Saharan dust intrusion in the Mediterranean."

Amiridis et al., (2013 and 2015) did not analyze the dust transport patterns. Amiridis et al (2013) describe the methodology for the pure-dust retrieval algorithm. Amiridis et al., (2015) describes the LIVAS database. The later paper focuses on the spectral conversion of the CALIPSO 532nm products for use in future ESA lidar missions that operate at 355 nm.

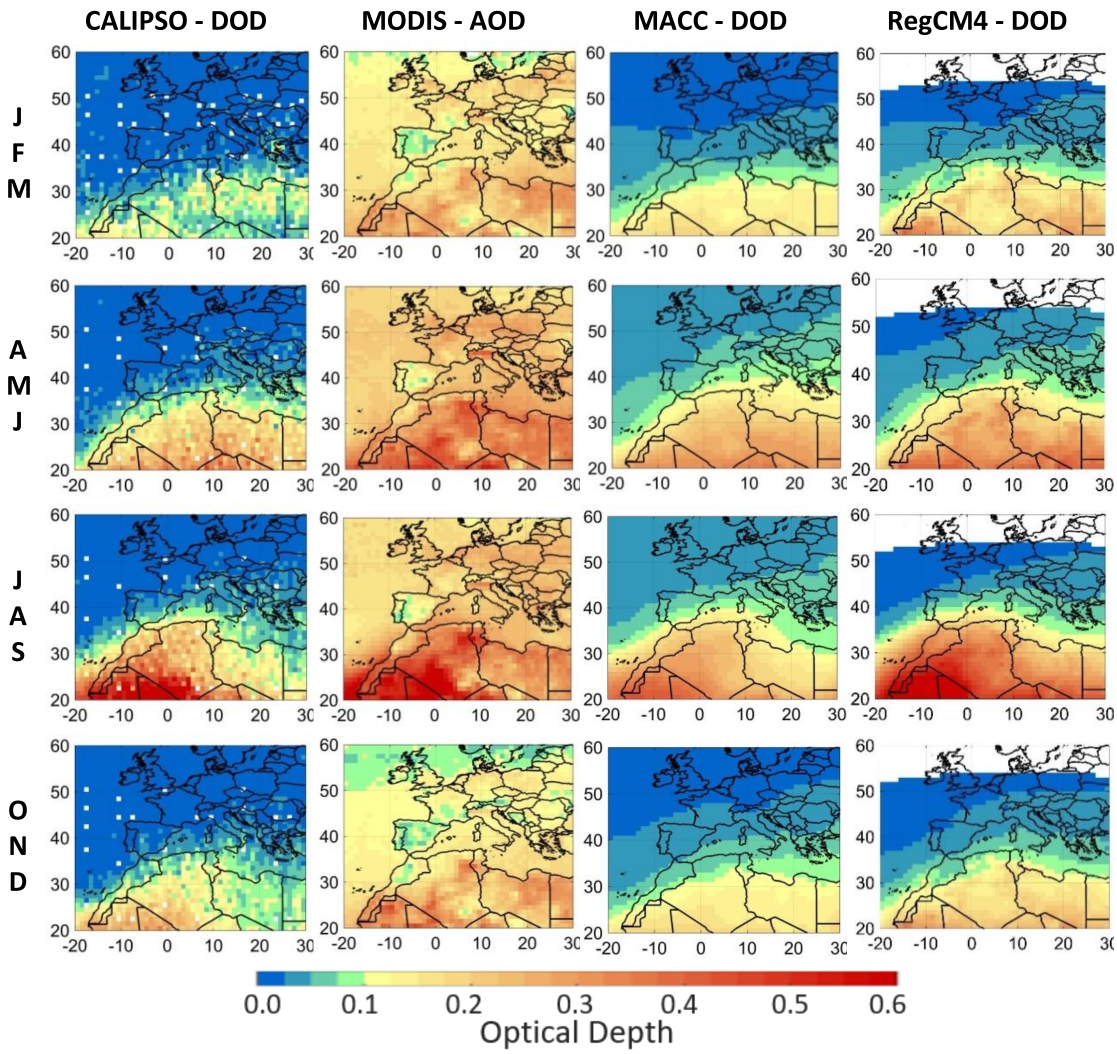
Sect. 3.1: It would be good if you can add a short comparison of the resulting DOD seasonal maps with the results of MODIS, MISR or any available reanalysis (as CAMS or MERRA).

[REPLY] We thank the reviewer for this comment. Therefore we calculated the optical depth using other available products such as the AOD from MODIS data and the DOD from MACC and RegCM4 models. We added a new figure, Figure 2, comparing our DOD seasonal maps with the ones produced with the above mentioned products, that is followed by a short discussion (page 10, line 26):

"In order to provide a more informative representation of the dust product presented here, we performed a comparison with MODIS AOD for the same period and the dust optical depth of the MACC reanalysis and a RegCM4 simulation for the period 2007-2012 and 2007-2014 respectively (Fig. 2). MODIS provides AOD for all natural and anthropogenic aerosol types. As a result the MODIS average value for the whole period and domain (0.267) is 281% almost three times, bigger than our product (0.095). It is noted thought that the values between the two satellite products are very similar over the Sahara desert. On the contrary, the corresponding average dust optical depth values of MACC (0.100) and RegCM4 simulations (0.104) reproduce better our product, since only dust is considered, though our product is lower by 5% and 8.6% respectively. Dust optical depth is overestimated over Europe and

Mediterranean by MACC and RegCM4 simulations in comparison to our product in all seasons and especially in the hot periods AMJ and JJA, but the reasons of these discrepancies have to be further studied.”

Figure 2: Comparison of the seasonal spatial distribution of the optical depth as received by (first column) pure-dust CALIPSO DOD product, (second column) MODIS AOD product, (third column) MACC reanalysis DOD product, (fourth column) RegCM4 simulated DOD product.



Sect. 3.2: In this case, you could compare your results from those obtained from EARLINET or models.

[REPLY] We thank the reviewer for this suggestion. We added the following paragraph in section 3.2 (page 11, line 29):

“In general, our results are in agreement with lidar-based studies which have been performed in several European sites. Papayannis et al. (2008) performed an exhaustive analysis on Saharan dust particles over Europe using EARLINET lidar profiles. They found that the dust layer center of mass extends from 3.0 to 3.8 km and the thickness ranges from 0.7 to 3.4 km. Specifically, Balis et al. (2012) calculated the mean base and top of dust layers in the eastern Mediterranean, Thessaloniki, to be around 2.5 ± 0.9 km and 4.2 ± 1.5 km, respectively. More recently, Mona et al. (2014) analyzed a long dataset of Saharan dust intrusions over Potenza, Italy, and found a mean layer centre of mass of 3.5 ± 1.5 km."

Sect 3.5: how do your results fit with those showed in Gkikas et al. (2016)?

[REPLY] In Gkikas et al. (2016) there is no discussion on the interannual variability of the dust events. The interannual variability of dust events is discussed in Gkikas et al. (2013). A sentence is added in the manuscript comparing our results to this work (page 15, line 32):

"Furthermore, over the same domain the decreasing trend of DOD coincides with the decrease of Saharan desert dust episodes as reported by Gkikas et al. (2013)."

Page 10 Line 28: Add Huneeus et al. (2016).

[REPLY] We added this reference.

Page 10 Line 30: "it is likely that the surface and elevated dust have different origins" sounds speculative. You could check this assumption with models or back trajectories.

[REPLY] The corresponding sentence is removed from the revised manuscript.

Figure 3. I would use the same colour palette than in Figure 4.

[REPLY] Figures 3 and 4 (new Figures 4 and 5) are based on the same color pallet with the difference that in Figure 4 a new restriction is introduced. In both cases, the black values represent the mean terrain elevation. In Figure 5, when we average the Con-DE, there is different sampling than the one used for the Clim-DE, and as a result, some means are produced from very few numbers of dusty observations (dO). In order to filter these case from the plot, so as the readers to concentrate on more significant features, we mask them with the new gray color. In order to better address these filters in the plots we changed the color pallet of Figure 5, and added a NaN black box (similar as in Figure 4), and labeled the gray box as "<4dO".

We also changed the manuscript when introducing the two figures:

In section 3.3 (page 12, line 11): "The median surface elevation is depicted with black colour (and is labeled as NaN) in the plots.

In section 3.4 (page 14, line 3): "Con-DE values derived from less than 4 dust observations (dO) in each cell are masked with grey colour (and are labeled as <4dO) in the plots. The median surface elevation is depicted with black colour (same as in Fig. 4)."

Figure 3. Could you provide any further explanation about the sharp transition over the Atlas?

[REPLY] We added the following sentence in the paper (page 12, line 32):

"The area south of Atlas Mountains (Fig. 4e, f, g, h) is characterized by haboob activity (Knippertz et al., 2009; Solomos et al., 2012). These systems are generated from convective outflows and contribute to the interannual burden of dust at this area."

Figures 3,4,5: Longitude and Latitude labels can be removed. They are too small.

[REPLY] The labels size is increased and it is more visible in the new version of the manuscript.

3D evolution of Saharan dust transport towards Europe based on a 9-year EARLINET-optimized CALIPSO dataset

Eleni Marinou[1,2], Vassilis Amiridis[1], Ioannis Binietoglou[1,3], Athanasios Tsikerdekis[5], Stavros Solomos[1], Emannouil Proestakis[1,4], Dimitra Konsta[1], Nikolaos Papagiannopoulos[6], Alexandra Tsekeri[1], Georgia Vlastou[8], Prodromos Zanis[5], Dimitrios Balis[2], Ulla Wandinger[7], and Albert Ansmann[7]

[1]IAASARS, National Observatory of Athens, Athens, 15236, Greece
[2]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
[3]National Institute of R&D for Optoelectronics, Magurele, Romania
[4]Laboratory of Atmospheric Physics, Department of Physics, University of Patras, 26500, Greece
[5]School of Geology, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
[6]Consiglio Nazionale delle Ricerche, Istituto di Metodologie per l'Analisi Ambientale (CNR-IMAA), Tito Scalo (PZ), Italy
[7]Leibniz Institute for Tropospheric Research, Leipzig, 04318, Germany
[8]Department of Physics, National and Kapodistrian University of Athens, Athens, Greece

Correspondence to: Eleni Marinou (elmarinou@noa.gr)

Abstract. In this study we ~~utilize~~ use a new dust product developed using CALIPSO observations and EARLINET measurements and methods to provide a 3D multiyear analysis on the evolution of Saharan dust over North Africa and Europe. The product ~~utilizes~~ uses CALIPSO L2 backscatter product corrected with a depolarization-based method to separate pure dust in external aerosol mixtures and a~~n adjusted~~ Saharan dust lidar ratio based on long-term EARLINET measurements. The methodology is applied on a nine-year CALIPSO dataset (2007-2015) and the results are analyz~~s~~ed here to reveal for the first time the 3D dust evolution and the seasonal patterns of dust over its transportation paths from the Sahara towards the Mediterranean and Continental Europe. During spring, the spatial distribution of dust shows a uniform pattern ~~dust is uniformly distributed in the horizontal~~ over the Sahara desert. The dust transport over the Mediterranean Sea results ~~o~~in mean Dust Optical Depth (DOD) values up to~~of~~ 0.1. During summer, the dust activity is mostly shifted to the western part of the desert where mean DOD near the source is up to 0.6. Elevated dust plumes with mean extinction values between 10 - 75 Mm^{-1} are observed throughout the year at various heights between 2 - 6 ~~km~~km, extending up to latitudes of 40° N. Dust advection is identified even at latitudes of about 60° N, but this is due to rare events of episodic nature. Dust plumes of high DOD are also observed above Balkans during the winter period and above North-West Europe during autumn at heights between 2 - 4 km~~km~~, reaching mean extinction values up to 50 Mm^{-1}. The dataset is considered unique with respect to its potential applications, including the evaluation of dust transport models and the estimation of cloud condensation and ice nuclei concentration profiles (CCN/IN). Finally, the product can be used to study dust dynamics during transportation, since it is capable of revealing even fine dynamical features such as the particle uplifting and deposition on European mountainous ridges such as the Alps and Carpathian Mountains~~Alps and Carpathian~~.

1 Introduction

Mineral dust is ubiquitous in the atmosphere and one of the main contributors to the global aerosol ~~burden~~ load (Zender et al., 2004; Textor et al., 2006), with almost half of the global dust emissions generated in Africa (Huneuus et al., 2011). This has large consequences for air quality downwind (Viana et al., 2002; Gobbi et al., 2007), ~~as well as~~ for the radiative budget due to scattering, absorption, and emission of solar and terrestrial radiation (Balkanski et al., 2007), as well as for ~~and~~ the cloud formation and lifetime (e.g., DeMott et al., 2003; Levin et al., 2005; Koren et al., 2010). T~~he nature of t~~hese effects depend~~s~~ strongly on the vertical distribution of dust. For example, ~~the absorbing~~ dust particles will have a stronger impact on shortwave radiation absorption when they are located above bright clouds (Yorks et al., 2009; Winker et al., 2013). Moreover, dust~~'s~~ atmospheric lifetime is much ~~larger~~ longer in the free troposphere than in the planetary boundary layer, and~~. U~~upon entering the free troposphere, dust particles can be transported across vast areas, altering the geographic pattern of their impacts (Prospero and Lamb, 2003; Levin et al., 2007; Ridley et al., 2012). Finally, the dust vertical distribution is crucial for dust-cloud interactions~~ studies~~ (e.g., Mamouri and Ansmann, 2016; Nickovic et al. 2016). Therefore, observing, monitoring and quantifying atmospheric dust burden and especially its vertical distribution is an important step towards understanding the climatic role of dust (IPCC, 2013, WG1, chapters 5, 7 and 9).

Lidar is the most prominent tool for aerosol profiling and has largely contributed to our knowledge of the vertical distribution of the dust optical properties (e.g., Liu et al. 2002; Ansmann et al., 2003; Balis et al., 2003; Papayannis et al., 2008; Mona et al., 2012; Granados-Muñoz et al. 2016; Bovchaliuk et al. 2016). Polarization ~~sensitive~~ lidar observations greatly expand the capabilities for dust detection ~~employing remote sensors~~, as non-spherical dust particles have a distinct signature on the particle depolarization ratio (e.g., Liu et al., 2008; Tesche et al., 2009). In Europe, the European Aerosol Research Lidar Network (EARLINET; Pappalardo et al., 2014) operates ~~sophisticated~~ advanced lidar systems employing depolarization techniques that have been invaluable for dust research. ~~Advanced~~ Sophisticated methodologies developed in EARLINET allow the complete characterization of different aerosol types including dust (e.g., Papayannis et al., 2008), as well as the ~~but also the discrimination of~~ dust contribution to the total aerosol load (Tesche et al., 2009).

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) mission equipped with the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument has been delivering ~~global~~ aerosol and cloud profiles across the globe for more than ten years ~~now~~ (Winker et al., 2009). This dataset offers the possibility to characterize the three-dimensional spatial distribution of aerosol as well as its temporal ~~and spatial~~ variation. CALIPSO ~~has been~~is established as an accurate and robust mean~~s~~ ~~of identifying~~for mineral dust identification from space (Liu et al., 2008; Omar et al., 2009). The application of EARLINET methodologies on CALIPSO observations can improve the observations for mineral dust research, as already suggested and applied in Amiridis et al. (2013). Specifically, this study retrieves the extinction of ~~a~~ pure dust ~~extinction~~ with high accuracy from CALIPSO, applying the depolarization-based separation method introduced by Tesche et al. (2009), coupled with the inference of a regionally uniform climatological LR (lidar ratio) for calculating dust extinction. This The latter value comes from long-term EARLINET measurements (Wandinger et al., 2010; Baars et al., 2016). It has been shown that the EARLINET-optimized CALIPSO dust product is in better agreement with Aerosol Robotic Network (AERONET) collocated measurements over Sahara and Europe and with Moderate Resolution Imaging Spectroradiometer (MODIS) measurements over the Mediterranean for collocated cells with low cloudiness (Amiridis et al., 2013). Thise product is considered as the first accurate dust retrieval from space, since dust discrimination methods applied on passive sensors are based on the separation of the fine from coarse particle mode (e.g., Kaufman et al., 2005), delivering mostly biased DODs over the oceans due to the contamination of the coarse mode by sea-salt particles (Su et al., 2013). One moreAnother advantage of the EARLINET-optimized CALIPSO dust product is its capability to provide equally accurate dust retrievals over all surface types, as since the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) ustilizes its own light source, overcoming the surface reflectance limitations of passive sensors (e.g., Hsu et al. 2004; Sayer et al., 2012).

Many studies have ustilizedd satellite observations to study derive dust properties over the Mediterranean during the last 15 years. Most of them focused on the horizontal dust distribution of dust using passive remote sensing techniques. Specifically, Aerosol Optical Depth (AOD) data and other columnar aerosol properties have been used extensively to study dust using satellites such as SeaWIFS (Sea-Viewing Wide Field-of-View Sensor; Antoine and Nobileau, 2006), TOMS (Total Ozone Mapping Spectrometer; e.g., Alpert and Ganor, 2001; Israelevich et al., 2002), MODIS (Moderate Resolution Imaging Spectroradiometer; e.g., Barnaba and Gobbi, 2004; Papayannis et al., 2005; Kosmopoulos et al., 2008; Papadimas et al., 2008), OMI (Ozone Monitoring Instrument; e.g., Marey et al., 2011) and MISR (Multi-angle Imaging SpectroRadiometer; e.g., Marey et al., 2011).Antoine and Nobileau, (2006) used SeaWIFS (Sea-Viewing Wide Field-of-View Sensor) observations to study the seasonal evolution and variability of dust aerosols over the broader Mediterranean Sea during the period 1998-2004. Alpert and Ganor (2001) and Israelevich et al. (2002) used the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) product in order to study the concentration of dust over Middle East and the dust sources of Northern Africa, respectively. The MODIS instrument, onboard both Terra and Aqua satellites has been extensively useded in studies of airborne mineral dust over the Mediterranean basin. Barnaba and Gobbi (2004) analysed one-year (2001) MODIS/Terra AOD at 550 nm observations and reported on the spatial distribution and seasonal variability of aerosols, including dust, over the Southern Europe, with a focus over the Mediterranean region. Papayannis et al. (2005) used MODIS/Terra data synergistically with lidar measurements and dust model simulations and investigated the vertical distribution of aerosols during dust outbreaks over Greece. also Kosmopoulos et al. (2008) and Papadimas et al. (2008) used MODIS/Terra and MODIS/Aqua to investigate the seasonal and interannual variability of AOD at 550 nm over Athens (Greece) and over the broader Mediterranean Sea, respectively. Marey et al. (2011) analysed ten-years of MODIS data synergistically with MISR and OMI and they produced a monthly climatology of aerosols over a domain covering the Nile Delta and northeast Africa. With respect to CALIPSO, the 3D distribution of dust and its optical properties have been studied for specific cases 3D dust observations from CALIPSO are used occasionally for case studies analyses (e.g., Amiridis et al., 2009; Mamouri et al., 2009; Marey et al., 2011; de Meij et al., 2012; Nabat et al., 2012, 2013; Mamouri and Ansmann, 2015). Moreover, Winker et al. (2013) provided a 3D global aerosol climatology from five-year CALIPSO data, along with the global distribution of mineral dust, derived using the ratio of columnar dust AOD to total AOD. ~~Moreover, several~~ Other studies offering~~ed~~ a global view of desert dust using CALIPSO are provided in ~~(~~Liu et al.~~,~~ (2008a;~~,~~ 2008b)~~;~~, Adams et al. (~~,~~2012)~~;~~, Yang et al. (~~,~~2012)~~;~~, Tsamalis et al. (~~,~~2013)~~;~~, Huang et al. (~~,~~2015a;~~,~~ 2015b) and~~;~~ Gkikas et al. (~~, 2015~~2016). In particular, the studies of Liu et al. (2008b), Yang et al. (2012) and Tsamalis et al. (2013) examined the transatlantic Saharan dust transport focusing on the optical properties of dust, the influence of nearby clouds and the vertical distribution of the Saharan Air Layer (SAL), respectively. Huang et al. (2015a) assessed the inferred most probable heights of global dust and introduced a separation method (Huang et al., 2015b) of anthropogenic dust (produced by human activities on disturbed soils) and free-tropospheric dust using CALIPSO and MODIS products. ~~The studies of~~ Liu et al. (2008a), Adams et al. (2012) and Gkikas et al. (~~2015~~2016) used CALIPSO observations in order to demonstrate the vertical structure of dust globally and/or above the Mediterranean ~~respectively~~. All the aforementioned studies ~~were~~ are based on standard CALIPSO products ~~which have~~with known limitations in accurately typing and quantifying the optical properties of pure dust (Wandinger et al., 2010; Tesche et al., 2013). The EARLINET-optimized dust CALIPSO product presented herein, was used in Georgoulias et al. (2016a) ~~One study used the EARLINET-optimized dust CALIPSO product~~ to apply aerosol typing on MODIS and derive an aerosol climatology over the Eastern Mediterranean ~~(Georgoulias et al., 2016)~~.

To our knowledge, this is the first time that a 3D pure-dust dataset is statistically analyzed over the area of North Africa and Europe in order to provide not only the horizontal but also the vertical patterns of Saharan dust intrusion in the Mediterranean. ~~large scale statistics of discriminated and optimized dust extinction and AOD fields from CALIPSO have not been provided to the literature yet. This paper aims to bridge this gap focusing on the vertical distribution of Saharan dust over North Africa and its transport towards Europe.~~ The study domain is from 20° to 60° N and from 20° W to 30° E. More specifically, we investigate the 3D inter-seasonal variation and intensity of dust transport patterns along with the inter-annual variations of DOD above this region ~~are investigated along with the inter-annual variations~~. The paper is organized as follows: i~~I~~n Sect. 2 the CALIPSO lidar data are briefly introduced and the pure dust retrieval scheme is described in detail. In Sect. 3, the main findings are presented and discussed:~~.~~ Initially, the inter-seasonal variation and intensity of dust transport patterns (e.g. DOD, dust layer heights) ~~are examined and information on dust layer heights~~ are presented (Sect. 3.1-3.3), ~~followed by~~and the representative extinction coefficient values inside the dust plumes are derived (Sect. 3.4). In Sect. 3.5, the inter-annual variation of dust is ~~presented~~ examined while our summary and concluding remarks are given in Sect. 4.

2 Data and methodology

2.1. CALIPSO product

CALIOP, flying on-board the joint NASA/CNES CALIPSO satellite, delivers global aerosol and cloud profiles since June 2006 (Winker et al., 2009). CALIOP measures aerosol backscatter profiles at 532 nm and 1064 nm, including parallel and perpendicular polarized components at 532 nm, at high horizontal and vertical resolution. The~~se~~ data are processed to Level 2 (L2) products, ~~including~~ providing aerosol and cloud backscatter and extinction coefficients at 532 nm and 1064 nm, as well as the linear particle depolarization ratio at 532 nm (Winker et al., 2009). First, Tthe processing algorithm , incorporated in the retrieval of the optical properties, separates the atmospheric scene in distinct atmospheric layers (i.e. aerosol, cloud, surface returns; Vaughan et al., 2009). Then, Ffor each aerosol layer the algorithm determines an aerosol subtype (i.e. dust, polluted dust, clean continental, polluted continental, marine, and smoke) based on a combination of information, such as the surface type, the layer integrated attenuated backscatter, the depolarization ratio at 532 nm and the aerosol layer height (Omar et al., 2009). The inferred subtype is used to assign derive the appropriate lidar ratio for each atmospheric altitude, a crucial input for the subsequent aerosol extinction retrieval (Young and Vaughan, 2009). Burton et al. (2013) showed an 80% successful detection of dust from CALIPSO, upon comparison to underflights with the HSRL system of NASA. This score is considered very high for aerosol typing purposes and is attributed to the depolarization measurement capability of the CALIOP sensor. FinallyFinally, the L2 products are aggregated to a gridded monthly-mean Level 3 (L3) product, providing mean profiles of extinction at 532 nm and mean AOD at a 2° × 5° spatial grid resolution (Winker et al, 2013). The most recent version of the L3 product (Version 3), released in October 2015, includes the correction of theed AOD calculation fromof cloudy scenes, the improved averaging of individual types as proposed by Amiridis et al. (2013) and Liu et al. (2008a), and corrections of signal artifacts responsible for high and low biases as also observed in Papagiannopoulos et al. (2016).

2.2. EARLINET-optimized CALISPSO product

In this study, we make use of the EARLINET-optimized pure dust extinction product, monthly--averageds at a horizontal resolution of 1° × 1° of the EARLINET-optimized pure dust extinction product, based on the methodology suggested bydescribed in Amiridis et al. (2013). This product is one of thea prominent outcomes of from the EARLINET-ESA collaboration to fordevelop the LIVAS database (LIdar climatology of Vertical Aerosol Structure for space-based lidar simulation studies; ((Amiridis et al., 2015). Unlike the original CALIPSO L3 product of 2° × 5° resolution, the 1- degree resolution of LIVAS has been proved very useful in supporting studies of the same spatial resolution, specifically for the retrievals from passive satellite sensors and model evaluation studies (e.g., Popp et al. 2016, Georgoulias et al., 2016, Tsikerdekis et al., 20162017). In our methodology, the pure dust backscatter coefficient (β_d) is decoupled from the total aerosol backscatter (β_p) based on depolarization measurements (δ_p), assuming a particle depolarization ratio (δ_p) value for pure dust (δ_d) equal to 0.31 (Tesche et al., 2009). Typical dust δ_{pd} values measured measured by with lidars methods for atmospheric dust in field campaigns around the globe are generally consistent with this value, showing little variation independently of the source region, showing little variation (e.g., Sakai et al., 2000; Liu et al., 2008b; Freudenthaler et al., 2009; Groß et al., 2011; Burton et al., 2012; Burton et al., 2013; Groß et al., 2013; Groß et al., 2015; Illingworth et al., 2015). During SAMUM 1 and 2 campaigns Saharan dust $\delta_p$$\delta_{nd}$ values varied between 0.27 and 0.35 at 532 nm (Ansmann et al., 2011), introducing 4% error in our calculations for the dust separated backscatter values, introducing 11% error in our calculations for the dust separated backscatter values. Based on this technique Using this separation technique, we avoid the use relying on of the polluted dust and dust aerosol types used in CALIPSO, and thus, eliminate possible misclassifications found in CALIPSO L2 product (Burton et al., 2013). A final correction is related to the particle linear depolarization ratio, which is recalculated from L2 perpendicular and total backscatter profiles, to improve the accuracy compared to the original CALIPSO L2-Version 3 product, ~~which has a known~~affected from a known bug (Tesche et al., 2013; Amiridis et al., 2013).

The quality control procedures and filtering criteria applied in the dataset are summarized in Table 1. In brief, CALIPSO L3 version 3 screening procedure is followed (Winker et al., 2013; CALIPSO L3-V3, 2015~~http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/data_summaries/l3/CALIOP_L3Products_3-00_v01.php~~), and additional filters are ~~inserted~~ incorporated to ensure the use of only cloud-free profiles. The additional methodology is as follows:

a) We remove ~~A~~all profiles ~~having~~ with cloud features anywhere in the column ~~are also removed~~.

b) We remove ~~T~~allhe profiles which fulfil the L3 CALIPSO “CAD score” or “Cirrus fringes” filters ~~are removed~~ (see also Table 1).

The pure dust extinction coefficient is computed ~~by~~ usingtilizing a lidar ratio of 55 sr instead of 40 sr used in the CALIPSO product (Omar et al., 2009; Lopes et al., 2013). This value is representative of dust over Europe, mainly originating from Northwest Africa, as measured in coordinated CALIPSO/EARLINET measurements (Pappalardo et al., 2010; Wanginder et al., 2011), and is in excellent agreement with recent studies of dust measurements both near the source (Tesche et al., 2009; Veselovskii et al., 2016) and during long range transport (Preißler et al., 2011; Kanitz et al., 2013; Gross et al., 2015; Baars et al., 2016; Papagiannopoulos et al., 2016). The individual backscatter coefficient profiles at 532 nm are aggregated at a horizontal spatial resolution of 1° × 1° and a vertical resolution of 60 m from -0.5 ~~km~~km to 20.2 km~~km~~ and 180 m~~m~~ from 20.2 km~~km~~ to 30.1 km~~km~~. Height is referenced to above sea level (a.s.l.) altitudes.

2.3. Climatological vs Conditional dust product

In this study, we calculate two separate dust products, the climatological and the conditional:

The climatological dust product is based on Amiridis et al. (2013), ~~where~~ with a value of 0 ~~km^{-1}~~km^{-1} ~~is~~ assigned to the non-dust aerosol types when averaging within a cell. This product, hereinafter, is referred ~~to~~ as Climatological Dust Extinction (Clim-DE) and the corresponding AOD as Dust AOD (DOD), and is presented and discussed in Sect. 3.1-3.3. As already discussed in the introduction, this product has been evaluated against ~~Aerosol Robotic Network (~~AERONET~~)~~ data and is in very good agreement with collocated measurements over Sahara and Europe (Amiridis et al., 2013). ~~and t~~The averaging methodology has been ~~also~~ adapted by the L3~~, -~~V3 CALIPSO product.

The conditional dust product is ~~calculated~~ derived ~~by~~ from averaging the CALIPSO dust extinction coefficients ~~for all cases where~~where dust is present, ignoring non-dust observations in the area. In particular, ~~when deriving the mean dust extinction coefficient~~ the clear air and non-dust aerosol types detected in the cell are ignored (set as NaN values when averaging). This product is referred to as Conditional Dust Extinction coefficient product (Con-DE) and is presented and discussed in Sect. 3.4.

The two products can be used for~~are provided for~~ different ~~applications~~applications: ~~.~~For example, Clim-DE is representative of the dust contribution to the total aerosol load and ~~. It can be used~~can be valuable ~~for~~in climatological studies. Moreover, ~~, especially when compared to the total AOD values of a region. For example~~the~~,~~ near-surface DOD ~~dust contribution given provided~~ by this product ~~could be used to provide estimates~~helps to estimate ~~of~~ the natural aerosol contribution in the total aerosol load close ~~to the total particle concentrations at~~to the surface for air-quality applications. The Con-DE product on the other hand, provides a measure of the intensity of the dust plumes. ~~However, the dust extinction profiles reported for Con-DE should be used with caution, since they frequently exceed the total extinction values in a cell.~~

2.4 Dust product uncertainties

The sources of uncertainties for the pure-dust product are discussed in this section. CALIOP is able to detect aerosol layers with $AOD > 0.005$ and $\beta > 0.25\ Mm^{-1}\ sr^{-1}$ (Winker et al. 2009). The uncertainty estimation of particulate backscatter, extinction and AOD retrievals reported in the CALIPSO Level 2, Version 3 Data Release, are based on the simplified assumption that all the uncertainties are random, uncorrelated and produced no biases (Young, 2010). More specifically, ignoring multiple scattering, the errors in the layer optical depth calculations typically arise from three main sources: (a) signal-to-noise ratio within a layer, (b) calibration accuracy, and (c) the accuracy of the lidar ratio used for the extinction retrieval. The lidar ratio uncertainty is the dominant contributor to the total uncertainties, and the relative error in the layer optical depth is always at least as large as the relative error in the lidar ratio of the layer, and grows as the solution propagates through the layer (CALIPSO L2-V3, 2010). In our dataset the typical uncertainties in the CALIPSO Level 2 version 3

product are between 30% and 100% for the AOD, between 30% and 160% for the aerosol backscatter and extinction coefficient and > 100% for the particle depolarization ratio.

Several studies report that CALIPSO underestimates the columnar AOD due to undetected aerosol in the free atmosphere. For instance, Rogers et al. (2014) report a ~ 0.02 AOD CALIPSO underestimation, when compared to collocated airborne HSRL measurements over the North American and Caribbean regions at night. In their data, the dust layers were primarily non-opaque with extinction less than $1\ km^{-1}$ so there were negligible multiple scattering effects. The aforementioned detection limits and uncertainties of CALIPSO products are propagated to the dust product presented here.

As already described, the EARLINET-optimized CALIPSO dust product is derived using the depolarization-based separation method, coupled with the selection of a uniform climatological LR value. These steps introduces uncertainties in the pure dust product. In particular, the uncertainty in the selection of the representative LR (55 ± 11) is 20% for the study area (e.g. Wandinger et al. 2010; Baars et al. 2016 and references within). ~~s~~This ~~value~~uncertainty in LR is less than half of the uncertainty of the generic LR in CALIPSO version 3 product ~~that~~(40 ± 20 for dust layers and 55 ± 22 for polluted dust layers). As already addressed in several studies (e.g. Wandinger et al. 2010; Schuster et al. 2012; Amiridis et al. 2013), CALIPSO V3 dust extinction coefficient and AOD values are about 30% lower than those obtained from collocated ground-based Raman lidar retrievals due to the low LR used in the CALIPSO aerosol retrievals. Amiridis et al. (2013) applied the EARLINET LR for the pure dust CALIPSO cases above North Africa and Europe, and compared with synchronous and collocated AERONET measurements. The results showed an absolute bias on the AOD of the order of - 0.03, improving on the statistically significant biases of the order of - 0.10 reported in the literature for the original CALIPSO product. The bias of - 0.03 is similar to the low bias of CALIPSO's column AOD due to undetected aerosol layers. In Kim et al. (2017), they found a global mean undetected layer AOD of 0.0031 ± 0.052 by comparing 2 year of CALIPSO (L1-V4) and MODIS AODs.

Regarding the error induced from the application of the dust separation method, this might be due to the selection of the particle depolarization ratio of dust and the other aerosol types (marine, anthropogenic or smoke). Tesche et al. (2009; 2011) and Ansmann et al. (2012) estimated that the uncertainty in dust related backscatter coefficients is 15-20% in well-detected dessert dust layers and 20-30% in less pronounce aerosol layers. Moreover, we have calculated that the uncertainty of the dust occurrences presented in Sec. 3.1 ("% Dust / Used Overpasses"), might be up to 8% in latitudes away from the sources, induced from the error in the selection of the δ_{nd} value (0.03±0.04). Finally, an uncertainty induced in the dust product presented in this work, originates from the CALIPSO subtype selection algorithm. In this version of our product, both dust and polluted dust observations are considered polluted dust, and the pure dust component is separated using the dust separation method. The other aerosol layers, which are characterised as clean marine (CM), smoke (S), polluted continental (PC) or clean continental (CC) are considered to be cases clear of dust and are not tested for a dust component. This introduces negligible error in our analysis and is expected to induce a negative bias in the parameter "% Dust / Used Overpasses" less than 8%, mainly in areas above sea. In general, Clim-DE and Cond-DE products, the uncertainty of the dust extinction values close to the surface and at high latitudes is < 54%. At high altitudes and for latitudes up to 45°N, the uncertainty of the values is < 20%. Nevertheless, the standard deviation of the climatological products, coming from the natural variability of the dust events, may exceed to a large extent the uncertainty of the retrieval, reaching values as high as 100% and 200%.

In the latest release of CALIPSO Level 2 version 4 product (CALIPSO L2-V4, 2016), based on CALIPSO team announcement, the accuracy of the original CALIPSO product is increased and the uncertainty is reduced. This version is based on a revised calibration approach which leads to an increase in the total attenuated backscatter coefficients by ~3% overall as compared to the version 3 values (CALIPSO L1-V4, 2016). Several bugs are fixed and a major overhaul of the aerosol subtyping algorithms along with revisions on the lidar ratio selections is applied.

2.5 Additional Satellite and Model dataset

The 6th version level-3 MODIS/Terra is a 1°x1° gridded aerosol dataset that is acquired from the NASA Giovanni system (https://giovanni.sci.gsfc.nasa.gov/giovanni/). In the current study the MODIS combined dataset, that takes into account the dark target (dark surface) and deep blue (bright surface) measurements, of aerosol optical depth was used for the period 2007 to 2015 (Sayer et al., 2014). Over the Mediterranean MODIS/Terra v6 was evaluated against 23 AERONET stations and was proven to score better that its predecessor MODIS/Terra v5 (Georgoulias et al., 2016).

The MACC global dataset is a reanalysis product based on the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecast (ECMWF) coupled with the chemistry transport model MOZART-3 (Kinnison et al. 2007). The horizontal resolution of the model is 80km and it uses 60 vertical levels from the surface up to 0.1hPa. MACC was used in a numerous gas phase and particulate matter studies (Innes et al., 2013; Katragkou et., 2014; Eskes et al., 2015; Flemming et al., 2015; Cuevas et al., 2015; Georgoulias et al., 2017). The dust optical depth data used in this study covers the period

2007-2012 and all MACC data are open to the public (http://apps.ecmwf.int/datasets/data/macc-reanalysis/levtype=sfc/). RegCM4 is an open source area-limited, sigma-p vertical coordinated regional climate model (Giorgi et al., 2012) based on the hydrostatic core of the PSU/NCAR Mesoscale Model (MM5; Grell et al., 1994). The simulation used in the current study is a part of a previous research where the dust optical depth of the model was evaluated against the dust climatological product of this work, after it was fully spatially and temporally collocated with the exact flyby of CALIPSO (Tsikerdekis et al., 2017). The simulation covers the period 2007 to 2014 with a horizontal resolution of 50km and 18 vertical sigma-p levels.

3 Results and discussion

In Sect. 3.1 - 3.4, we examine the inter-seasonal variation and intensity of dust transport patterns, from 2007 to 2015, for the domain 20° W to 30° E and 20° N to 60° N. In Sect. 3.1 we provide the average climatological state of the seasonal dust distribution at a spatial resolution of 1° × 1°. In Sect. 3.2 we give information on dust layer heights. In Sect. 3.3, we illustrate the mean climatological vertical structure of dust reaching Europe. To achieve that, the area of study is separated into five longitudinal zones with a step of 10°. In Sect. 3.4, we illustrate the vertical intensity of the dust plumes, using again longitudinal zone maps. Finally, in Sect. 3.5, we examine the inter-annual variation of dust.

3.1 Horizontal dust distribution

In this section, we provide the average climatological state of the seasonal horizontal dust distribution derived from CALIPSO dust product ~~over period 2007-2015~~ at a spatial resolution of 1° × 1° for the domain of North Africa and Europe. The seasonal grouping used in this study is as follows: from January to March (JFM), from April to June (AMJ), from July to September (JAS) and from October to December (OND). In our study region, March and October are considered transition months for Saharan dust advection (e.g., Ganor, E., 1994; Guirado et al. 2014). This grouping is based on the dominant patterns revealed from the maps of monthly mean DODs (not shown). More specific, the decision is based on the observation that the events during February–March and October–November, although ~~more~~ rarer, are usually more intense than those of the other months. This is further supported from a ten year (2001 – 2011) analysis of African dust outbreak PM_{10} observations over the Mediterranean basin (Pey et al., 2013).

Figure 1 shows the geographical distribution of dust occurrences (Figs. 1a, c, e, g) and the corresponding mean DOD values ~~(Figs. 1b, d, f, h) of~~ for each season (Figs. 1b, d, f, h).~~.~~ In order to provide a more quantitative representation of the dataset, the domain is aggregated in six areas over the study region.~~,~~ The main results and statistical parameters are provided in Table 2. In particular, the information provided is: the mean and standard deviation of the DOD, the maximum values along with the 95% percentile in parenthesis, the layer's centre of mass and top height along with their standard deviations (these parameters are discussed in the next section), the percentage of the observations with DOD greater than zero in the cloud-free observations (with 100% as unity), the percentage of the cloud-free occurrences in the total observations provided by the CALIPSO product (with 100% as unity) and each domain's geographic extent.

Table 2 shows the impact of cloud contamination in our dataset. During AMJ, JAS and OND, more than 80% of the total observations are cloud-free above North Africa. Above Central-East Mediterranean (C-E Med.), more than 80% of the total observations are cloud-free and above Central West Mediterranean (C-W Med.) approximately 60% - 80% of the total observations are cloud-free. With increasing latitude, the cloud-free sampling is reduced to percentages of ~ 40% - 60% in latitudes greater than 45° N. During JFM, cloudy conditions restrict our dataset in the greatest extent. During the same period, the cloud-free cases used represent ~ 80% of the total observations above North Africa, approximately 60 - 70% of the total observations above the Mediterranean and ~ 30% in the domain between 45° N - 60° N. In the areas (and seasons) where clouds do not dominate (e.g. 70% clear-sky conditions), our cloud-free product is considered representative of the dust distribution. In areas where cloudy skies dominate (e.g. 30% clear-sky conditions), the clear-sky CALIPSO profiles cannot be considered as representative of all meteorological conditions, so the results should be used with caution.

Based on Fig. 1 and Table 2, the overall percentages of dust occurrences and ~~of the~~ mean DOD values are ~~larger~~ greater during summer and spring months. ~~, while~~ D~~d~~uring autumn and winter the emission and transport of dust towards Europe is suppressed due to the more effective removal processes and due to the atmospheric dynamics ~~-~~favouring the transport of dust towards the Atlantic (e.g. ~~(~~Israelevich et al., 2002; Schepanski et al., 2009). More specific, during JFM (Figs. 1a, b) limited dust activity is observed almost uniformly over the Sahara desert. The ~~AOD~~ DOD remains roughly over the entire study domain below 0.~~2~~13 with 75% of the observations having DODs < 0.17, 95% of the observation having DODs < 0.5 and extreme values with DODs ~2. ~~a standard deviation lower than 0.3.~~ The dust occurrences decrease with latitude and the presence of dust is approximately 7~~8~~0 % over Africa and the Mediterranean region and decreases to lower than 50 % over northern Europe. The most affected area during these months is eastern Mediterranean. The cyclone formation over the central Mediterranean, which is affected by mid-latitude depressions generated either in the Atlantic Ocean or in north-western Europe (e.g., Trigo et al., 1999; Maheras et al., 2001), results in the transportation of dust from the Libyan Desert towards the Balkans which leads to dust occurrences up to ~~80~~ 70 % (Fig. 1a) along with mean seasonal DOD of 0.1-0.2 (Fig. 1b). In the domains between 10° E - 30° E and 30° N - 40° N, 5% of the dust events are observed with DODs > 0.41, 1% with DODs >0.95 and extreme observations with DODs are up to 1.6. Similar mean values have been reported in the literature for this period, along with extreme events characterized by AOD values higher than 1 (Gerasopoulos et al., 2011). Moving northward, mean DOD tends ~~to~~ decrease due to the increasing distance from the major dust sources and also due to higher precipitation at the northern parts of the study region that efficiently removes dust from the atmosphere (e.g., Moulin et al., 1998; Marrioti et al., 2002).

During AMJ (Figs 1c, d) dust production occurring over the entire Saharan desert ~~and~~ with mean DOD values ~~exceeding~~ of 0.~~4~~ 26 ± 0.26 ~~along with~~and occurrences ~~up to~~of ~~80~~86~~-90~~ %, ~~are found~~ uniformly at latitudes between 20° N and 30° N. The activated dust sources are located in the broad “dust belt” and are usually associated with topographical lows in the arid regions~~,~~ ~~with land adjacent to strong topographical heights~~ and with the intermountain basins (Prospero et al., 2002). The arrival of mid latitude extratropical cyclone systems from the Atlantic Ocean as well as cyclogenesis at the Gulf of Genoa and/or at northern African coast favours dust transport over central and eastern Mediterranean. Mean DOD over these areas reaches values of 0.12 ± 0.20~~0.15~~ (Fig. 1d)~~) with~~ and extreme observations observed with DODs up to 2.74. Dust is also present over central and northern Europe with occurrence percentages between ~~30~~ 65 % and ~~50~~ 53 % (Fig. 1c; Table 2), revealing that dust particles can be transported far away from their sources under favourable meteorological conditions.

During JAS (Figs. 1e, f), intense dust activity is largely shifted to the western part of the Sahara where dust occurrences ~~reach almost 100~~are >90 % and mean DOD near the sources ~~is~~ up to 0.6 (Fig. 1f). In the domain between 10° W - 00° and 20° N - 35° N, the mean DOD is 0.43, with 25% of the dust observations having DODs > 0.69, 5% >1.2 and the extreme DODs up to 3 (Table 2). The migration of the ITCZ (Intertropical Convergence Zone) towards higher latitudes and the dominance of trade wind patterns (easterlies) benefit the transportation of dust towards the Atlantic Ocean as seen also by the westward plumes in Figs. 1e and 1f. In the same period, ~~I~~increased dust occurrences (~~up to 95~~ 83 %) are also found over Western Mediterranean and South Italy. In the domain between 10° W - 00° and 35° N - 45° N, the mean DODs are 0.09 ±,0.14 with 5% of the dust observations having DODs >0.55 and extremes DODs up to 2.3.~~and mean DOD values (up to 0.2) during JAS are also found over western Mediterranean and South Italy.~~

During OND dust activity is significantly suppressed (Fig. 1g) except from the south-west desert areas close to the Sahel where mean DOD lies in the range 0.~~3~~2-0.~~4~~ 3 (Fig. 1h). In the domain between 10° W - 00° and 20° N - 30° N, the mean DODs are 0.43 ± 0.39 and extremes DODs up to 3 (Table 2)).~~The associated standard deviation is comparable to the DOD values. In general high values of DOD during spring and summer months over the dust sources correspond to high values of standard deviation up to 0.5. Low values of DOD over northern latitudes and during winter and autumn months are associated with low variations and the standard deviation is lower than 0.05.~~

In order to provide a more informative representation of the dust product presented here, we performed a comparison with MODIS AOD for the same period and the dust optical depth of the MACC reanalysis and a RegCM4 simulation for the period 2007-2012 and 2007-2014 respectively (Fig. 2). MODIS provides AOD for all natural and anthropogenic aerosol types. As a result the MODIS average value for the whole period and domain (0.267) is 281% -almost three times, bigger than our product (0.095). It is noted thought that the values between the two satellite products are very similar over the Sahara desert. On the contrary, the corresponding average dust optical depth values of MACC (0.100) and RegCM4 simulations (0.104) reproduce better our product, since only dust is considered, though our product is lower by 5% and 8.6% respectively. Dust optical depth is overestimated over Europe and Mediterranean by MACC and RegCM4 simulations in comparison to our product in all seasons and especially in the hot periods AMJ and JJA, but the reasons of these discrepancies have to be further studied.

3.2 Vertical dust distribution

CALIPSO offers the ability to assess the vertical distribution of dust from space. To facilitate the investigation of the vertical characteristics of dust, two parameters are introduced, the dust Top Height (TH) and the dust Centre of Mass height (CoM) (Mona et al., 2006; Mona et al., 2014; Binietoglou et al., 2015). TH is defined as the height corresponding to the altitude where the 98 % of the dust extinction lies below. CoM is estimated by the calculation of the extinction-weighted altitude given by the formula:

$$CoM = \frac{\int_{z_t}^{z_b} z a(z) dz}{\int_{z_t}^{z_b} a(z) dz}, \quad (1)$$

where z_b and z_t are the base and top altitude of the dust feature respectively. α denotes the ~~aerosol~~ dust extinction coefficient at altitude z. The estimate of CoM provides information related to the altitude where the most part of the dust load is located. This parameter is considered ideal for comparisons with aerosol layer height retrievals from passive remote sensing (e.g., IASI, GOME-2A, Sentinel5P and the future Sentinel-4 and Sentinel-5 missions (Ingmann et al. 2012)), since these retrievals are sensitive to the location of the dust mass maximum within the layer (e.g., TROPOMI Aerosol Layer Height product; Sanders et al. 2015).

Figure ~~2~~ 3 shows the spatial distribution of TH and CoM for the four seasons. In Table 2, the TH and CoM values (a.s.e.) are accompanied with their standard deviations providing an indication of the variability of the dust heights in the atmosphere of the study area. During JFM dust resides in general below 3 km~~km~~ a.s.e. (above surface elevation) over land with CoM at about 1.3 ± 1.6 km ~~km~~ a.s.e. (Figs. ~~2a~~3a, b). Over the sea, several transport paths are discernible especially over eastern Mediterranean with dust tops ~~extending~~ traveling ~~higher than2~~ at 2.3 ± 1.9 km ~~km~~ a.s.e. During AMJ, TH and CoM are up to 4.2 ± 1.7~~5~~ km~~km~~ and around 2.4 ± 1.1~~2~~ km ~~km~~ a.s.e. respectively over eastern parts of Sahara. Over the Mediterranean Sea and South Europe dust tops extend around 2-3.5 km ~~km~~ and CoM around 1-2 km ~~km~~ a.s.e., with Centre and East Mediterranean having the most elevated plumes (Figs. ~~2c~~3c, d). The latitudinal slope of CoM denotes the latitudinal transport of dust during AMJ from south to north. The highest TH values (>4.5 km~~km~~) are found during the warm period (JAS) over north-western Africa and over the adjacent Atlantic Ocean region (Figs. ~~2e~~3e, f). This is most likely attributed to the intrusion of the lower tropospheric Atlantic monsoon, south of the ITCZ, and the development of MCS (mesoscale convective systems) that favour the elevation of dust at this area (Bou Karam et al., 2008). The dust height decreases towards the eastern part of the study region. ~~.~~ In the interim, the dominance of the strong Saharan high enables the mobilization of dust from western part of Sahara towards western Mediterranean and Europe. This pattern leads to elevated dust ~~between~~ at 3.0 ± 1.7~~2-4~~ km ~~km~~ a.s.e. and CoM at 1.6 ± 1.1 ~~~1.5~~ km ~~km~~ a.s.e. over south European countries and Balkans. During OND the horizontal pattern ~~situation~~ is similar to JJA however with much lower heights (Figs. ~~2g~~3g, h).

In general, our results are in agreement with lidar-based studies which have been performed in several European sites. Papayannis et al. (2008) performed an exhaustive analysis on Saharan dust particles over Europe using EARLINET lidar profiles. They found that the dust layer center of mass extends from 3.0 to 3.8 km and the thickness ranges from 0.7 to 3.4 km. Specifically, Balis et al. (2012) calculated the mean base and top of dust layers in the eastern Mediterranean, Thessaloniki, to be around 2.5 ± 0.9 km and 4.2 ± 1.5 km, respectively. More recently, Mona et al. (2014) analyzed a long dataset of Saharan dust intrusions over Potenza, Italy, and found a mean layer centre of mass of 3.5 ± 1.5 km.

3.3 Climatological ~~Vertical~~ dust cross sections

To further illustrate the vertical dynamics of dust reaching Europe, the area of study between 20° W and 30° E is separated into five longitudinal zones of 10° interval, covering latitudes from 20° to 60° N. The vertical structure of the averaged

Climatological Dust Extinction coefficient (Clim-DE) for each of these five longitudinal zones (illustrated in Fig. ~~3~~ 4 as latitude-height cross-sections) reveal several dust layers and strong seasonal variations. The two dashed lines are drawn such as to show how many dust observations are averaged for the extinction retrievals. The extinction values below the higher dashed line have been calculated by averaging a number of dust observations, greater than 18 (2 dust overpasses per season and year). The extinction values below the lower dashed line have been calculated by averaging a number of dust observations greater than 54 (2 dust overpasses per month and year). The median surface elevation is depicted with black colour (and is labeled as NaN) in the plots. In general dust is always ubiquitous at heights close to the surface throughout the year. The lower layers are representative of near source dust activity and boundary layer processes. The spring and summer peaks indicate the increased activity of Saharan ~~a mobilisation of the~~ dust sources ~~in the area during these months~~ (Moulin et al., 1998; Schepanski et al., 2007). More specific, for the area between 10° W and 20° W over the Atlantic extending from Africa to west of Spain and Ireland~~England~~, the presence of elevated dust plumes is evident (Figs. ~~3a~~4a-d) mainly during summer and for latitudes up to 30°N. During JFM the plume is located below 2 km~~km~~ height a.s.l. (above sea level), while from spring to autumn the plume reaches a height of 5 km~~km~~ a.s.l. and yields high values of extinction coefficient (~75 Mm^{-1}) over Africa. Over the area from 0° to 10° W, extending from western Algeria, Morocco, Spain, and the British Isles ~~England~~ we found Clim-DE values inside the Africa mixing layer greater than ~~50~~ 60 Mm^{-1} for all seasons. Maximum values of extinction are observed during summer months when dust is elevated up to 6 km ~~km~~ with Clim-DE values around 120 ± 140 Mm^{-1} above N. Africa and mean values exceeding 200 Mm^{-1} above the Algerian Desert (Fig. ~~3g~~4g). These findings are in good agreement with more than two years of AERONET observations in Tamanrasset site, a strategic site for dust research located in the heart of Sahara (Guirado et al., 2014). A steep decrease in extinction values is observed along the African coastline with values of 20 Mm^{-1} above the southern part of the Iberian Peninsula (38°-42° N) where dust is trapped by the Pyrenees. The distinct decrease of extinction values across the African coastline is an indication that dust is always present inside the rather deep Saharan boundary layer while it is only occasionally transferred towards the Mediterranean when atmospheric dynamics favor this kind of flow. At higher latitudes, the CALIPSO dust extinction is drastically reduced but still observed in ranges of 1-2 km~~km~~ a.s.l. and with mean Clim-DE values of 5 Mm^{-1}. ~~Moving eastwards (0°-10° E) dust extends as far as the North Sea (50°-60° N) with mean Clim-DE values of 5 Mm^{-1} (Figs. 3i-j).~~ Moving eastwards (0°-10° E)~~E~~ elevated dust is trapped topographically by the Alps (47°-52° N) with ~~significantly high~~ values >10 Mm^{-1}. As the dust-laden air-masses approach the mountains, they decelerate and thus the dust concentration increases (Israelevich et al., 2012). Maximum values of extinction (>50 Mm^{-1}) are observed over northern Africa during summer (Fig. ~~3k~~4k). Close to the Algerian sources, south of the Atlas Mountains (~30° N) extinction coefficient is greater than 200 Mm^{-1} close to the surface (Fig. 3k). The area south of Atlas Mountains (Fig. 4e, f, g, h) is characterized by haboob activity (Knippertz et al., 2009; Solomos et al., 2012). These systems are generated from convective outflows and contribute ~~in~~ to the interannual burden of dust at this area. As dust extends to higher latitudes (30°-40° N) Clim-DE decreases (<75 Mm^{-1}). Over the area between 10°-20° E (Figs. 4~~3~~m-p), similar patterns are observed. This region includes the dust sources of Libya and central Sahara, central Mediterranean, the eastern Alps and part of North Europe. It is evident from this figure that dust extinction over central Mediterranean (35°-45° N) is around 25

Mm^{-1}throughout the year. As in the previous western zonal section the same pattern over the Alps is encountered. Moving further eastwards maximum values of Clim-DE are found during spring. At the most eastern part of the study area (20°-30° E; Figs. 3q4q-t), dust is trapped by the Carpathian Mountains (45°-49°N) especially during winter, thus highlighting, once more, the role of topography. Significant dust presence is evident all over the zonal section (until 60° N) mostly attributable to elevated dust traveling along with the westerlies from western and central parts of Europe towards East. Above the Balkans and during JFM values of 29 ± 65 Mm^{-1} are observed in the first 1.5 km, and 10 ± 30 Mm^{-1} between 2.5 – 3.5 km. In AMJ and JAS respectively, means of ~ 16 ± 40 Mm^{-1} and ~ 9 ± 20 Mm^{-1} are observed in altitudes between 1.5 to 5 km. The values of Clim-DE are higher (>45 Mm^{-1}) over Africa during winter and spring, in relation with the ones observed during the other two seasons (<45 Mm^{-1}), and reach higher altitudes (5-6 km km a.s.l.) during spring and summer. In summary, the obtained cross-sections for the five longitudinal zones indicate that higher extinction coefficient values are observed near the source and at low altitudes, where dust particles are efficiently deposited. Above NE Africa, Tthe dominant Clim-DE values are >45 Mm^{-1} above Africa throughout the yearr in altitudes up to 2 km a.s.l. during JFM and up to 4 km during AMJ and JJA. Moreover, the standard deviation of the means is around 130% at the altitudes up to 2 km and ~100% between 2 – 4 km, at all seasons. Above West Africa, the extreme Clim-DE values observed during JAS in the altitudes up to 2 km are 113 ± 131 Mm^{-1}. In C-E Mediterranean, dust is always present, with maximum extinctions during AMJ, reaching 27 ± 54 Mm^{-1} close to the surface and ~ 18 ± 30 Mm^{-1} during JAS and OND. In C-W Mediterranean, the highest means of JAS are ~16 ± 40 Mm^{-1}. and >75 M above West Africa during JAS. In South Europe and Mediterranean, the dominant values are >10 M in the first 2 km a.s.l. and ~30 M close to the surface. For latitudes greater than 45° N, and during AMJ mean values around of 855 ± 27 Mm^{-1} are 4 ± 16 Mm^{-1} are the most common.observed close to the surface above NE Europe and NW Europe respectively.

The above results can be used to also estimate also the airborne mass concentration of dust. and the impact on cloud formation. The dust mass concentration M_d can be obtained from the optical properties of dust using the following relationship (Mamouri and Ansmann, 2014):

$$M_d = \rho_d(\upsilon_d/\tau_d)\alpha_d \qquad (2)$$

Dust particle density, ρ_d, is assumed to be 2.6 g cm^{-3} (Ansmann et al., 2012). The conversion factor for dust volume to extinction ratio, υ_d/τ_d, is assumed to be 0.64 x 10^{-6} m (Mamouri and Ansmann, to be submitted in AMT SALTRACE SI). α_d is the dust extinction coefficient.

The dust mass concentration can be obtained from the optical properties of dust with an uncertainty of 20-30% (Ansmann et al., 2012; Mamouri and Ansmann, 2014). For example, the Clim-DE values imply dust mass concentration >75 $\mu g\ m^{-3}$ above Africa throughout the year and >125 $\mu g\ m^{-3}$ above West Africa during JAS. In South Europe and Mediterranean, the corresponding values are >17 $\mu g\ m^{-3}$ in the first 2 kmkm a.s.l. and ~50 $\mu g\ m^{-3}$ close to the surface. For latitudes greater than 45° N, values around 8 $\mu g\ m^{-3}$ are the most common. The, the decreasing intensity with height and latitude found in the Clim-DE product is representative of the average dust distribution over the area. However, this behaviour is not may not be representative for of the distribution during dust episodes over Europe. This is because since the extinction coefficient values presented in Fig. 34 for the Clim-DE product result are produced byfrom averagingthe mean ofpartially and fully dominated dust and non-dust episodescases. In order to describe the spatial patterns and the intensity of the dust plumes during episodes only, address this issue, we introduce and discuss the Con-DE product is discussed in the next section.

3.4 Conditional dust cross sections

In this section we examine the Conditional Dust Extinction coefficient (Con-DE) distribution. The two dashed lines in Fig. 4 5 correspond to the number of dust observations greater than 18 (2 dust overpasses per season and year) and greater than 54 (2 dust overpasses per month and year) for the lower and higher dashed line respectively. Con-DE values derived from less than 4 dust observations (dO) in each cell are masked with grey colour (and are labeled as <4dO) in the plots.NaN values). The median surface elevation is depicted with black colour (same as in Fig. 4). Con-DE values are significantly different from the Clim-DE, as seen in Fig. 34. Although Con-DE has similar values to Clim-DE near the sources, where dust is always present, above the Atlantic and the Mediterranean Con-DE is characterized by significantly higher values. This is because the two products differ mostly over areas which are not dominated by dust-. In the vertical cross sections of Fig. 4 5 the pattern of Con-DE shows two distinct dust featurespopulations of dust. For example over the longitudinal zone from 20° to 30° E during summer (Fig. 4o5o) two dust populations features are visible: one above North Africa extending from the surface to ~5 *km*km a.s.l. and another above the Mediterranean between 3 and 6 *km*km a.s.l. The two distinct layers are, also identified in other regions and in other seasons (e.g. Fig 5a, l, p, s, t). , These populations are linked are due to two different processes: the near surface dust at the southern parts of the study region represents fresh emissions from the dust sources, while the elevated plumes that extend northern until 40° N are due to the advection of dust, associated to the seasonality of the long-range transport paths (Lelieveld et al., 2002; Israelevich et al., 2012; Huneeus et al. 2016). This separation is enhanced as one moves from the west to the east sectors. At the western part of the domain (10°-20° W) the near surface and elevated dust originates probably from the same sources. As the two layers diverge (10° W to 30° E) it is likely that the surface and elevated dust have different origins (e.g. West Sahara, Bodélé, East Sahara). Similar double layer patterns are found in all seasons and over all areas with various characteristics. For example during JAS at the region extending from 0° to 10° W (Fig. 4g5g) the generation of dust from the source region is much more intense than the transportation term, which is also evident. For the same period, in the area 0° to 10° E the transportation term above the Mediterranean between 3 and 6 *km*km height, originating from the intensive source regions, becomes much more important than the source term at the same cross section.

The use of the particle depolarization ratio as a mean of estimating the age of dust from its state of mixing is supported by Fig. 5. Again, the two dashed lines in the figure correspond to the number of exceedances (NoE), NoE>18 and NoE>54. Particle depolarization ratio values derived from less than 4 dust observations in each cell are masked with grey colour (NaN values) and the median surface elevation is depicted with black colour. In Fig. 5 we see the mean depolarization corresponding to Fig. 4. As it can be seen, the depolarization is higher for air masses closer to the desert while it decreases as the air-masses travel towards Europe. This is due to the mixing of dust with other aerosol particles, which takes place after some days of transport.

~~However, the depolarization ratio cannot be considered as a possible age index, since it provides the mixing of dust with other particles (Tesche et al., 2009). It is used here as an age estimator only because the Sahara desert is away from Europe and the mixing of transported dust with anthropogenic particles takes place as soon as the plumes mix with anthropogenic particles over the European Continent.~~

Looking in more detail the vertical cross sections of Fig. ~~4~~5, we observe the rare but very intense elevated dust plumes during JFM (4a, e, ~~l~~i, m). During that period, dust is advected between 1.5–4 km~~km~~ height a.s.l. with Con-DE values >45 Mm^{-1} equivalent to dust mass concentrations >75$\mu g\ m^{-3}$. Furthermore, in Fig. ~~4q~~5q, the intensity of the JFM dust episodes above the Balkans is depicted. The Con-DE value in this domain is in the same range ~~with~~ as the one in the other regions at the same period, but the dust plumes can be thicker, extending from the ground until 4 km~~km~~ a.s.l. ~~-~~The trapping of Saharan dust from the mountainous ridges of Europe (located between 40°N – 50 °N, e.g. the Alps 45°N-48°N) is also evident by the Con-DE cross-sections(e.g. Fig. 5i, m). ~~. Accumulation of dust at the windward slopes results after t~~The deceleration of the transport air masses along the mountain ridges results to the accumulation of dust at the windward slopes. ~~-~~ ~~Increased~~ Dry deposition of dust ~~rates~~ at ~~this~~ these areas result also in the formation of "brown snow" and albedo reduction, with profound climatological implications (e.g., Fujita, 2007; Shahgedanova et al., 2013). This phenomenon is more intense during JFM period due to the advection of dust at~~in~~ lower heights. ~~at this period.~~

During AMJ (~~4b~~5b, f, j, n, r) and JAS (~~4c~~5c, g, k, o, s) the elevated dust above Mediterranean has Con-DE values of 35-50 Mm^{-1} (58-83 $\mu g\ m^{-3}$), in heights between 2-6 km~~km~~ and up to latitudes of 40° N. The transport of dust during AMJ is mostly due to the eastward propagation of N.Africa – Mediterranean low pressure systems (Sharav cyclones). Dust is embedded in the cyclonic circulation and the penetration to latitudes higher than 40°N is limited. For latitudes 40° and 50° N, during the warm seasons (AMJ and JAS), the Con-DE values inside the transported dust plumes ~~are~~ is between 20-40 Mm^{-1} everywhere (33-67 $\mu g\ m^{-3}$). Rare events, characterized by relatively higher Con-DE (>35 $Mm^{-1}$and >58 $\mu g\ m^{-3}$), between 2-5 km~~km~~ a.s.l., are observed over the British Isles and Germany during OND (Figs. 5~~4~~h, l~~i~~). These events, caused by the propagating low pressure systems over the East Atlantic, have been documented in detail from the EARLINET community reporting extinction coefficient values up to 200 Mm^{-1} inside dust plumes (Ansmann et al., 2003; Müller et al., 2003). In the vertical cross section of Fig. 5~~4~~ it is evident that dust reaches the upper levels of the troposphere (>8 km~~km~~ a.s.l.) with Con-DE values of ~10 Mm^{-1} in all longitudinal zones and during all seasons. Dust occurrence is very low, close to zero for heights greater than 8 km~~km~~ a.s.l. during spring and summer and for heights greater than 6 km~~km~~ a.s.l. during autumn and winter.). A quantitative representation of the Clim-DE and Con-DE products is provided in Table 3. In this, regional statistics on the two products, along with their standard deviation are provided for three altitudinal ranges (0 – 2, 2 – 4 and 4 – 6 km a.s.l.).

3.5 Interannual variability of dust

In this section we ~~utilize~~ use the CALIPSO derived monthly mean DOD values, for the total-column and for five individual layers (0.18–0.5, 0.5–1, 1–2, 2–4, 4–8 km~~km~~), to study their inter-annual variability during the 9 year period between 2007 and 2015. The selected layers are representative for both near surface and long-range transported dust plumes. The data are aggregated on a 10° x 10° cell over the study region. Using a first-order autoregressive linear regression model on the de-seasonalized monthly DOD values as described in Zanis et al. (2006), temporal trends of DOD were calculated. Figure ~~6~~ 6 shows the geographical distribution of de-seasonalized trends (~~year-1~~$year^{-1}$) for the columnar DOD (a) and for the five individual layers (b-f). Hatched filled grid cells depict the statistical significance trends with 99% confidence. A decrease ~ 0.001 yr^{-1}~~yr-1~~ (~ 4% yr^{-1}~~yr-1~~) is evident for the South European cells (0°-30° E, 40°–50° N) (with these values being > 95% statistically significant). Examination of the five vertical layers shows a similar decreasing pattern. The negative trends observed in the area (mainly above North Africa and Mediterranean), are additionally characterized by constant decrease throughout the layers, although the trends are not statistically significant. The small negative DOD trends (< 0.002 yr^{-1}~~yr-1~~ corresponds to < 5% yr^{-1}~~yr-1~~) coming from this temporal limited dataset, are in good agreement with the global decrease of dust estimated from an 161-year time series of dust from 1851 to 2011, created by projecting wind field pattern onto surface winds from a historical reanalysis in Evan et al. (2016), and also with the global mean near-surface dust concentration decrease by 1.2% yr^{-1}~~yr−1~~ reported in Shao et al. (2013) paleoclimate research for the period 1984-2012 (even though Europe and North America are excluded from their trend analysis). In comparison with studies relevant to the time period considered in this work, the DOD decrease of 0.001 yr^{-1} over the northern coast of Africa is in agreement with Floutsi et al. (2016), who based on 12 years of MODIS-Aqua observations (2002-2014) reported an average decrease of 0.003 yr^{-1} for the coarse mode fraction of AOD over the broader Mediterranean Sea. Furthermore, over the same domain the decreasing trend of DOD coincides with the decrease of Saharan desert dust episodes as reported by Gkikas et al. (2013). Regarding the AERONET stations over the domain of northern Africa and Europe, Yoon et al. (2012) reported on the trends of AOD at 440 nm along with the corresponding Ångström Exponents (440 and 870nm). The documented negative trends over the AERONET stations of Avignon (France), Dakar (Senegal) and Ispra (Italy) are in agreement with the negative DOD reported here, although with discrepancies in the magnitude, while trend disagreements are observed over the AERONET station of Banizoumbou (Niger). The decreasing trends of DOD observed over the domain northern of Africa and Europe coincide with the generally documented downward AOD trends reported based on several satellite observations of MODIS/Aqua, MODIS/Terra, MISR and SeaWiFS (Pozzer et al., 2015; de Meij et al., 2012; Hsu et al., 2012; Georgoulias et al. 2016b). More particular, in the most recent study of Georgoulias et al. (2016b), using MODIS/Terra and MODIS/Agua observations, they reported negative statistically significant trends over Algeria, Egypt and the Mediterranean and positive trends over Middle East. Overall, for the Mediterranean they reported an AOD trend of -0.0008 yr^{-1} for the MODIS/Terra observations (2000 – 2015) and -0.0020 $yr^{-1}$for the MODIS/Aqua observations (2002 – 2015), with the trends being statistical significant at the 95% confidence level in both cases. A possible increase is only found for west Sahara areas (10° - 0° W, 20°–30° N). However, the results for this cell are not considered statistical significant. In our study, we calculate the DOD trend along with the statistically significance of each trend for the period 2007-2015 (108 monthly values). Nine years are considered a small period for a robust trend calculation and it would be interesting to repeat the same analysis in the future to extended aerosol record. The de-seasonalization process as well as the trend are describing the examined period only. Figure 7 shows the DOD internal variability of the 20 individual areas, as it is calculated from monthly mean DODs. Is evident from this figure that the DOD values in 2008 are relatively higher than the other years and in almost all the domains bellow 40°N. Similarly, relatively high values are observed in some of these areas for the year 2010. Since these years are at the beginning of our study period, they have a significant contribution on the negative trends observed during the examined period.

4~~.~~ Summary and conclusions

An optimized CALIPSO dust product was recently developed with a regional correction of the Saharan dust lidar ratio~~LR~~ using EARLINET measurements (Amiridis et al., 2013). The same product has been u~~tiliz~~sed here to provide the three-dimensional dust distribution and its transport pathways across northern Africa and Europe. The monthly climatology of African dust obtained from 2007 to 2015 allows the description of the spatio-temporal features of dust properties. The study of the mean state climatology shows strong seasonal shifts in dust source regions and transportation pathways. The seasonal cycle of the dust transport is well captured with the lowest values of DOD in winter and the highest values in spring and summer. During summer and autumn, dust aerosols are more confined to the source region, while during spring significant dust aerosols from the Sahara are extended uniformly over North Sahara and are transported over the Mediterranean and Europe. Dust extinction coefficient, Centre of Mass and Top Height retrieved parameters are used to quantitatively understand the 3D evolution of dust and the seasonal differences in the vertical distribution which are evident as well. Over the source region of Sahara Desert, dust CoM and the TH are higher during spring and summer and lowest during winter. Dust transport mechanisms are more efficient during summer when dust is often lifted up to 6 *km*~~km~~, coinciding with the deepest dust layer. The appearance of localized regions of increased extinction coefficient values over mountains (the Alps, the Pyrenees, and the Carpathian Mountains) denotes the existence of aerosol transport routes that decelerate in front of the mountain ranges. Rare and intense events are observed above Balkans during winter period and above North-West Europe during autumn. The inter-annual analysis revealed that DOD trends during the study period are of the order of 0.001/year for the South European cells, showing constant decrease throughout the different layers.

The dust climatology presented here is of paramount importance in understanding the three-dimensional production and transport of Saharan dust which will contribute to better estimate the dust impacts on climate. The use of two products, the climatological and conditional in this study allowed us to conclude on both the dust contribution to the total aerosol load over our domain, but also on the intensity of the Saharan dust events recorded in the region. Future work includes: (i) the optimization of CALIPSO dust retrievals based on measured dust LR from ground-based lidars and particle depolarization ratio over extended regions of deserts in the Middle East and China, to obtain a robust global climatology of dust; (ii) the calculation of cloud condensation nuclei and ice nuclei concentrations from polarization lidar as suggested by Mamouri and Ansmann (2016), to provide a quantification of the climatic effect of dust on cloud formation.

5 Data availability

The CALIPSO data were obtained from the online archive of ICARE Data and Services center http://www.icare.univ-lille1.fr/archive (CALIPSO Science Team, 2015; ICARE Data Center, 2016). MODIS data are publicly available on the NASA Giovanni system (https://giovanni.sci.gsfc.nasa.gov/giovanni/). MACC data are publicly available on http://apps.ecmwf.int/datasets/data/macc-reanalysis/levtype=sfc/. The regional climate model ReGCM4 code is available at https://gforge.ictp.it/gf/project/regcm/frs/. RegCM4 simulation data used in this work are available upon request from Athanasios Tsikerdekis (tsike@geo.auth.gr). The LIVAS database is publicly available at http://lidar.space.noa.gr:8080/livas/. LIVAS EARLINET-optimized pure dust products are available upon request from Eleni Marinou (elmarinou@noa.gr) and Vasilis Amiridis (vamoir@noa.gr).

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Tables and Figures

Figure 1: Geographical distribution of the seasonal dust occurrences (a ,c ,e ,d) and the mean DAOD values (b ,d ,f ,h) for the three-month averages: January–March (a ,b), April-June (c ,d), July–September (e ,f), and October–November (g ,h), and the domain between 20° W-30° E and 20°-60° N for the period 2007-2015, measured with the CALIPSO climatological dust product.

Figure 2: Comparison of the seasonal spatial distribution of the optical depth as received by (first column) pure-dust CALIPSO DOD product, (second column) MODIS AOD product, (third column) MACC reanalysis DOD product, (fourth column) RegCM4 simulated DOD product.

Figure 23: Geographical distribution of the dust top height (a-d) and the center of mass (e-h) in kmkm a.s.e. measured with CALIPSO dust product for the three-month averages: January–March (a, e), April-June (b, f), July–September (c, g), and October–November (d, h), and the domain between 20° W-30° E and 20°-60° N for the period 2007-2015.

Figure 34: Geographical zonal distribution of the climatological dust extinction coefficient values (Mm^{-1}) measured by CALIPSO dust product for the regions 10° W to 20° W (a-d), 0° to 10° W (e-h), 0° to 10° E (i-l), 10° E to 20° E (m-p), and 20° E to 30° E (q-t) for the latitudinal regions from 10° N-60° N as illustrated by domain maps for the three-month averages: January–March (a, e, i, m, q), April-June (b, f, j, n, r), July–September (c, g, k, o, s), and October–November (d, h, l, p, t). The median surface elevation is depicted with black colour.

Figure 45: Geographical zonal distribution of the conditional dust extinction coefficient values (Mm^{-1}) measured by CALIPSO dust product for the regions 10° W to 20° W (a-d), 0° to 10° W (e-h), 0° to 10° E (i-l), 10° E to 20° E (m-p), and 20° E to 30° E (q-t) for the latitudinal regions from 10° N-60° N as illustrated by domain maps for the three-month averages: January–March (a, e, i, m, q), April-June (b, f, j, n, r), July–September (c, g, k, o, s), and October–November (d, h, l, p, t). The median terrain elevation is depicted with black colour.

Figure 5: Geographical zonal distribution of the conditional dust particle depolarization ratio measured by CALIPSO for the regions 10° W to 20° W (a-d), 0° to 10° W (e-h), 0° to 10° E (i-l), 10° E to 20° E (m-p), and 20° E to 30° E (q-t) for the latitudinal regions from 10° N-60° N as illustrated by domain maps for the three-month averages: January–March (a, e, i, m, q), April-June (b, f, j, n, r), July–September (c, g, k, o, s), and October–November (d, h, l, p, t). The median terrain elevation is depicted with black colour.

Figure 66: Geographical distribution of the de-seasonalized trends (yr^{-1}yr-1) derived from monthly columnar DOD (a) and for five individual layers (b-f), for the period 2007-2015, aggregated over 10° x 10° grid cells. Hatched filled grid cells depict the statistical significance trends with 99% confidence.

Figure 7: Interannual variability of the DODs for the 10° x 10° grid cells depicted in Fig. 6, for the period 2007-2015.

Table 1: Quality control procedures and filtering applied in CALIPSO data.

1.	Screen out all features that are not aerosols
2.	Set all clear air profile measurements to 0.0 km^{-1}~~km-1~~
3.	Samples below opaque cloud and aerosol layers are removed
4.	Clear-Sky Mode: Only measurements in which no clouds are in the column are considered
5.	Large negative near-surface extinction filter: all level 2 aerosol extinction samples adjacent to the surface having a value less than -0.2 km^{-1}~~km~~$^{-1}$ are ignored
6.	Samples where aerosol extinction uncertainty is less than 99.9 km^{-1}~~km-1~~ are allowed
7.	CAD score: Only features having cloud-aerosol discrimination (CAD) scores between -100 and -20 are used
8.	Only features having extinction QC flag values of 0, 1, 16, or 18 are allowed
9.	Cirrus Fringes: Misclassified cirrus in the upper troposphere, coming from CAD artifacts, are removed
10.	Remove measurements which are contaminated by surface values: extinction values near the surface less than −0.2 km^{-1}~~km-1~~ are ignored
11.	Undetected surface attached aerosol low bias filter (Changed between CALIPSO L3 version 1 and version 3): samples classified as “clear air” lying beneath the lowest quality screened aerosol layer whose base is below 250 m from the local surface are ignored
12.	Negative signal anomaly mitigation strategy: all level 2 aerosol extinction coefficients within 60 meters of the planetary surface are excluded from level 3 calculations (new in L3 version 3)
13.	All non-dust aerosol types detected in the cell are assigned with a value of 0.0 km^{-1}~~km-1~~
	<u>Extra filters with more strict cloud screening:</u>
14.	All profiles having cloud features anywhere in the column are removed
15.	All profiles which fulfil the L3 CALIPSO “CAD score” or “Cirrus fringes” filters are removed

Table 2: Regional statistics on mean dust optical depth, max values, dust layer center of mass (CoM) and top height (TH) (a. s. e.), ratio of dust observations to cloud-free observations, ratio of cloud-free observations to total observations and domain boundaries.

	DOD Mean ± St.dev.	DOD Max Vals. (Perc. 95%)	CoM ± St.dev.	Top Height ± St.dev.	Nr Dst in Nr cl-free	Nr cl-free in Nr obs.	Domain
NE Africa							[10E,30E] [20N,30N]
JFM	0.11 ± 0.17	2.19 (0.42)	1.5 ± 1.2	2.6 ± 1.8	0.72	0.84	
AMJ	0.26 ± 0.26	3.09 (0.73)	2.4 ± 1.1	4.2 ± 1.7	0.86	0.86	
JAS	0.18 ± 0.21	2.63 (0.56)	2.3 ± 1.0	4.0 ± 1.4	0.84	0.93	
OND	0.11 ± 0.14	2.93 (0.34)	1.9 ± 0.9	3.3 ± 1.4	0.81	0.93	
NW Africa							[10W,10E] [20N,35N]
JFM	0.13 ± 0.18	1.86 (0.47)	1.5 ± 1.3	2.4 ± 1.8	0.67	0.82	
AMJ	0.26 ± 0.26	2.31 (0.75)	2.2 ± 1.2	3.8 ± 1.6	0.86	0.83	
JAS	0.43 ± 0.39	3.03 (1.20)	2.9 ± 1.0	5.1 ± 1.3	0.94	0.88	
OND	0.22 ± 0.26	2.59 (0.71)	2.2 ± 1.0	3.9 ± 1.6	0.82	0.81	
C-E Med.							[10E,30E] [30N,45N]
JFM	0.09 ± 0.18	1.62 (0.41)	1.3 ± 1.4	2.3 ± 1.9	0.69	0.70	
AMJ	0.12 ± 0.20	2.74 (0.51)	1.8 ± 1.5	3.2 ± 2.1	0.82	0.76	
JAS	0.08 ± 0.12	1.80 (0.33)	1.6 ± 1.1	3.0 ± 1.7	0.89	0.96	
OND	0.08 ± 0.11	1.55 (0.31)	1.4 ± 1.1	2.7 ± 1.6	0.82	0.80	
C-W Med.							[10W,10E] [35N,45N]
JFM	0.03 ± 0.06	1.09 (0.11)	1.3 ± 1.6	2.0 ± 1.9	0.49	0.57	
AMJ	0.05 ± 0.10	1.35 (0.25)	1.8 ± 1.6	2.9 ± 2.2	0.65	0.61	
JAS	0.09 ± 0.14	2.33 (0.36)	1.9 ± 1.2	3.3 ± 1.8	0.75	0.80	
OND	0.05 ± 0.09	1.62 (0.20)	1.3 ± 1.2	2.3 ± 1.6	0.63	0.64	
NE Europe							[10E,30E] [45N,60N]
JFM	0.025 ± 0.055	0.97 (0.11)	1.2 ± 1.4	1.7 ± 1.7	0.37	0.28	
AMJ	0.033 ± 0.062	1.61 (0.12)	1.6 ± 1.2	2.5 ± 1.6	0.61	0.47	
JAS	0.032 ± 0.045	0.90 (0.11)	1.6 ± 1.1	2.7 ± 1.4	0.60	0.58	
OND	0.023 ± 0.043	0.50 (0.09)	1.2 ± 1.0	1.9 ± 1.4	0.49	0.43	
NW Europe							[10W,10E] [45N,60N]
JFM	0.015 ± 0.033	0.47 (0.06)	1.2 ± 1.6	1.7 ± 1.7	0.36	0.36	
AMJ	0.023 ± 0.037	0.73 (0.08)	1.5 ± 1.6	2.2 ± 1.9	0.52	0.47	
JAS	0.022 ± 0.042	0.93 (0.08)	1.4 ± 1.5	2.1 ± 1.7	0.43	0.52	
OND	0.018 ± 0.035	0.57 (0.07)	1.1 ± 1.2	1.7 ± 1.4	0.40	0.44	

Table 3: Regional statistics on the dust extinction coefficient for altitudes between 0 to 2km, 2 to 4 km and 4 to 6 km (a. s. l.).

	0 – 2 km	2 – 4 km	4 – 6 km	
	Clim-DE / Cond-DE / St. dev	**Clim-DE / Cond-DE / St. dev**	**Clim-DE / Cond-DE / St. dev**	**Domain**
NE Africa				
JFM	42 / 50 / 74 Mm^{-1}	-7 / 43 / 20 Mm^{-1}	0 / 25 / 5 Mm^{-1}	[10E,30E]
AMJ	66 / 66 / 88	44 / 53 / 48	18 / 48 / 26	[20N,30N]
JAS	42 / 42 / 64	30 / 40 / 37	13 / 43 / 22	
OND	34 / 34 / 51	17 / 32 / 24	3 / 27 / 9	
NW Africa				
JFM	46 / 60 / 80 Mm^{-1}	-6 / 45 / 18 Mm^{-1}	0 / 29 / 5 Mm^{-1}	[10W,10E]
AMJ	73 / 73 / 90	41 / 59 / 49	13 / 51 / 25	[20N,35N]
JAS	113 / 113 / 131	83 / 83 / 71	43 / 50 / 40	
OND	59 / 59 / 86	35 / 48 / 43	10 / 36 / 19	
C-E Med.				
JFM	22 / 44 / 55 Mm^{-1}	-4 / 48 / 16 Mm^{-1}	0 / 31 / 5 Mm^{-1}	[10E,30E]
AMJ	27 / 35 / 54	17 / 52 / 34	5 / 42 / 15	[30N,45N]
JAS	18 / 18 / 28	13 / 33 / 22	4 / 37 / 12	
OND	19 / 23 / 32	10 / 35 / 19	2 / 27 / 7	
C-W Med.				
JFM	5 / 24 / 33 Mm^{-1}	1 / 32 / 7 Mm^{-1}	0 / 21 / 2 Mm^{-1}	[10W,10E]
AMJ	10 / 23 / 38	6 / 35 / 19	1 / 31 / 8	[35N,45N]
JAS	16 / 22 / 40	13 / 33 / 23	5 / 38 / 14	
OND	10 / 22 / 33	4 / 29 / 14	0 / 29 / 4	
NE Europe				
JFM	4 / 37 / 41 Mm^{-1}	0 / 29 / 5 Mm^{-1}	0 / 15 / 1 Mm^{-1}	[10E,30E]
AMJ	8 / 17 / 27	2 / 21 / 17	0 / 14 / 2	[45N,60N]
JAS	7 / 14 / 21	2 / 16 / 9	0 / 16 / 2	
OND	4 / 16 / 19	1 / 21 / 6	0 / 14 / 1	
NW Europe				
JFM	1 / 16 / 16 Mm^{-1}	0 / 16 / 2 Mm^{-1}	0 / 15 / 1 Mm^{-1}	[10W,10E]
AMJ	4 / 16 / 16	1 / 21 / 11	0 / 14 / 2	[45N,60N]
JAS	3 / 15 / 15	1 / 22 / 7	0 / 18 / 2	
OND	2 / 16 / 15	0 / 23 / 4	0 / 13 / 0	

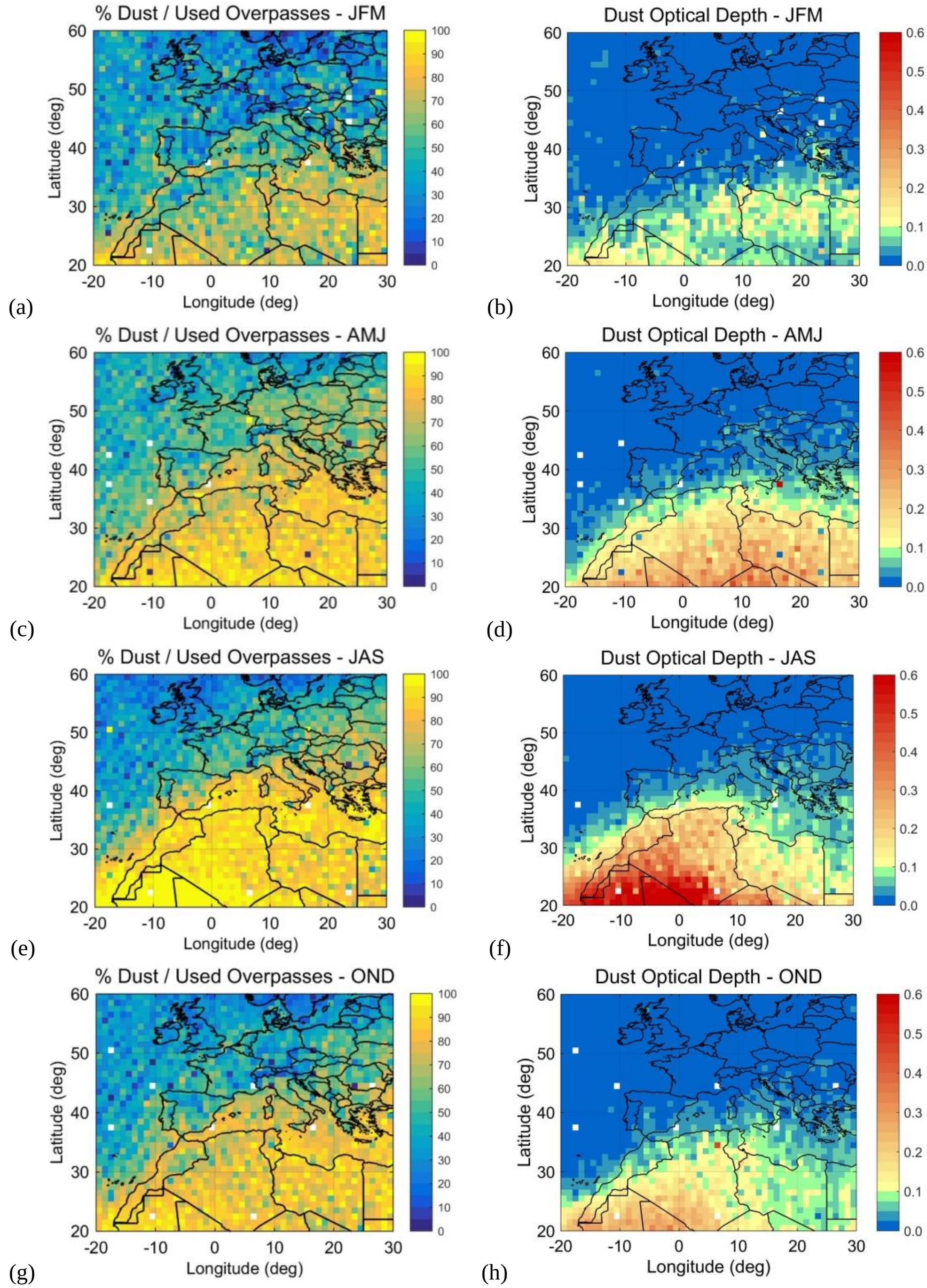

% Dust / Used Overpasses - JFM
Dust Optical Depth - JFM
% Dust / Used Overpasses - AMJ
Dust Optical Depth - AMJ
% Dust / Used Overpasses - JAS
Dust Optical Depth - JAS
% Dust / Used Overpasses - OND
Dust Optical Depth - OND
Latitude (deg)
Longitude (deg)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

Fig.1

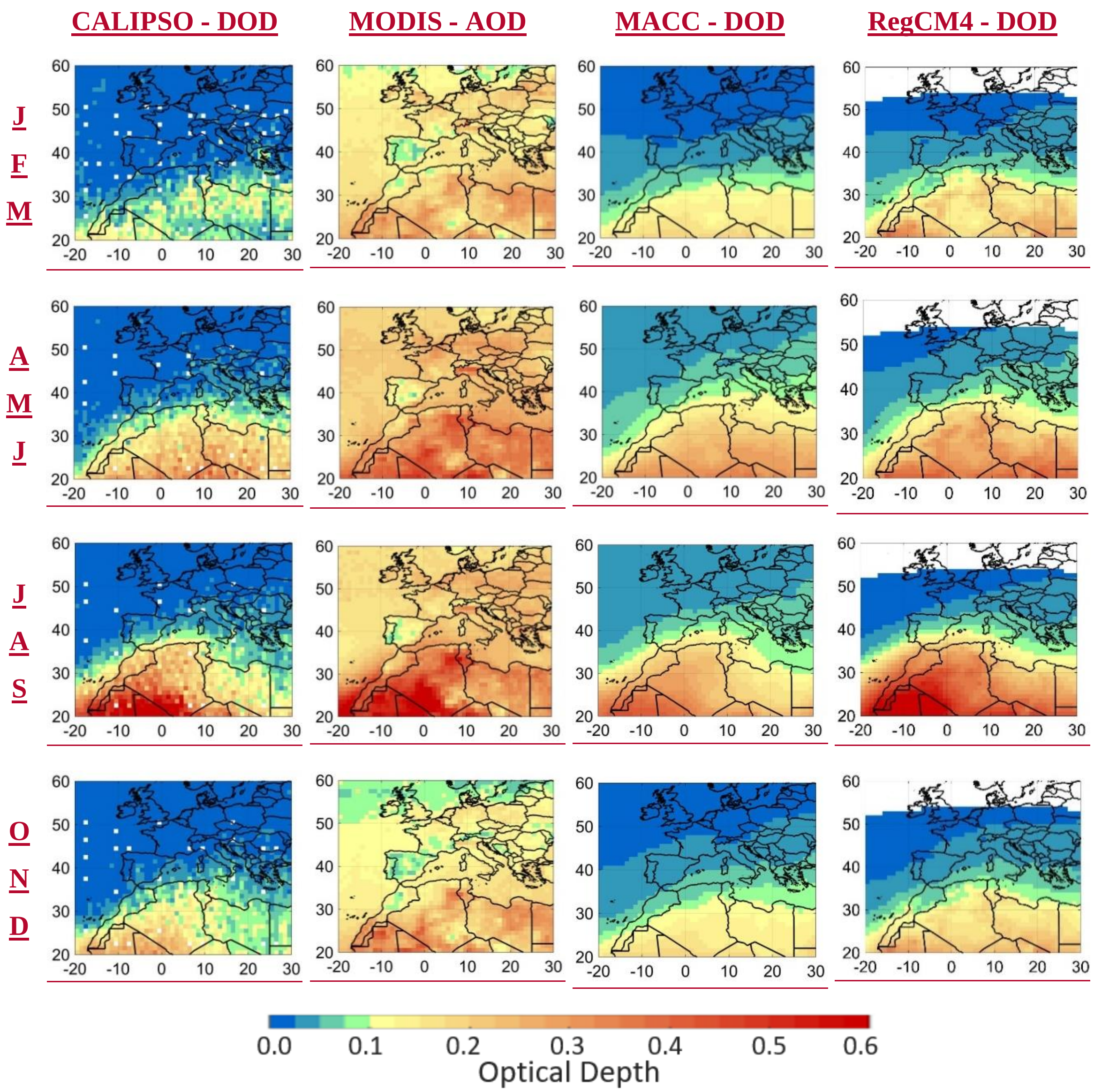
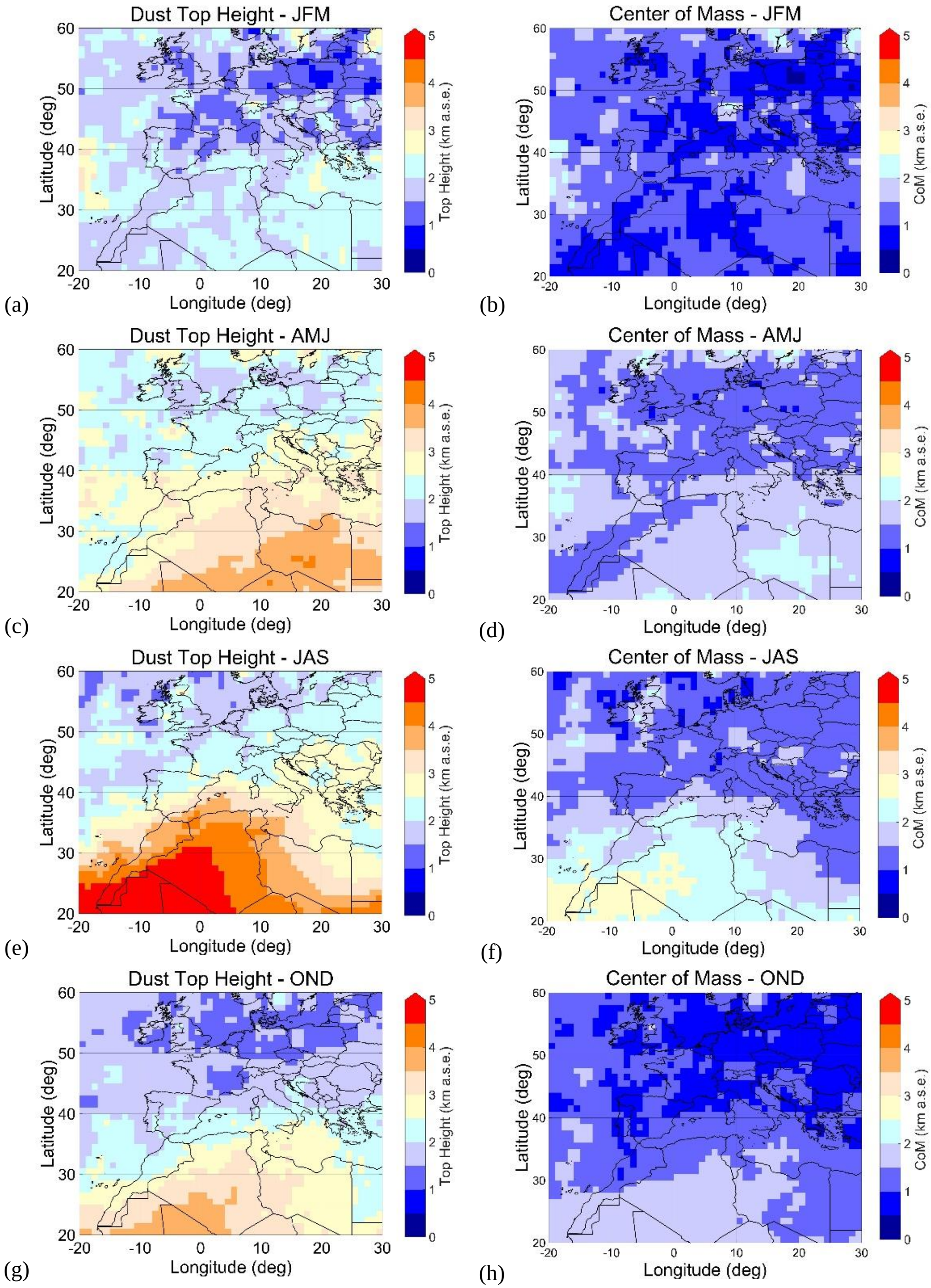

CALIPSO - DOD
MODIS - AOD
MACC - DOD
RegCM4 - DOD
J F M
A M J
J A S
O N D
0.0 0.1 0.2 0.3 0.4 0.5 0.6
Optical Depth

Fig.2



Dust Top Height - JFM
Center of Mass - JFM
Dust Top Height - AMJ
Center of Mass - AMJ
Dust Top Height - JAS
Center of Mass - JAS
Dust Top Height - OND
Center of Mass - OND
Latitude (deg)
Longitude (deg)
Top Height (km a.s.e.)
CoM (km a.s.e.)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

Fig.~~2~~3

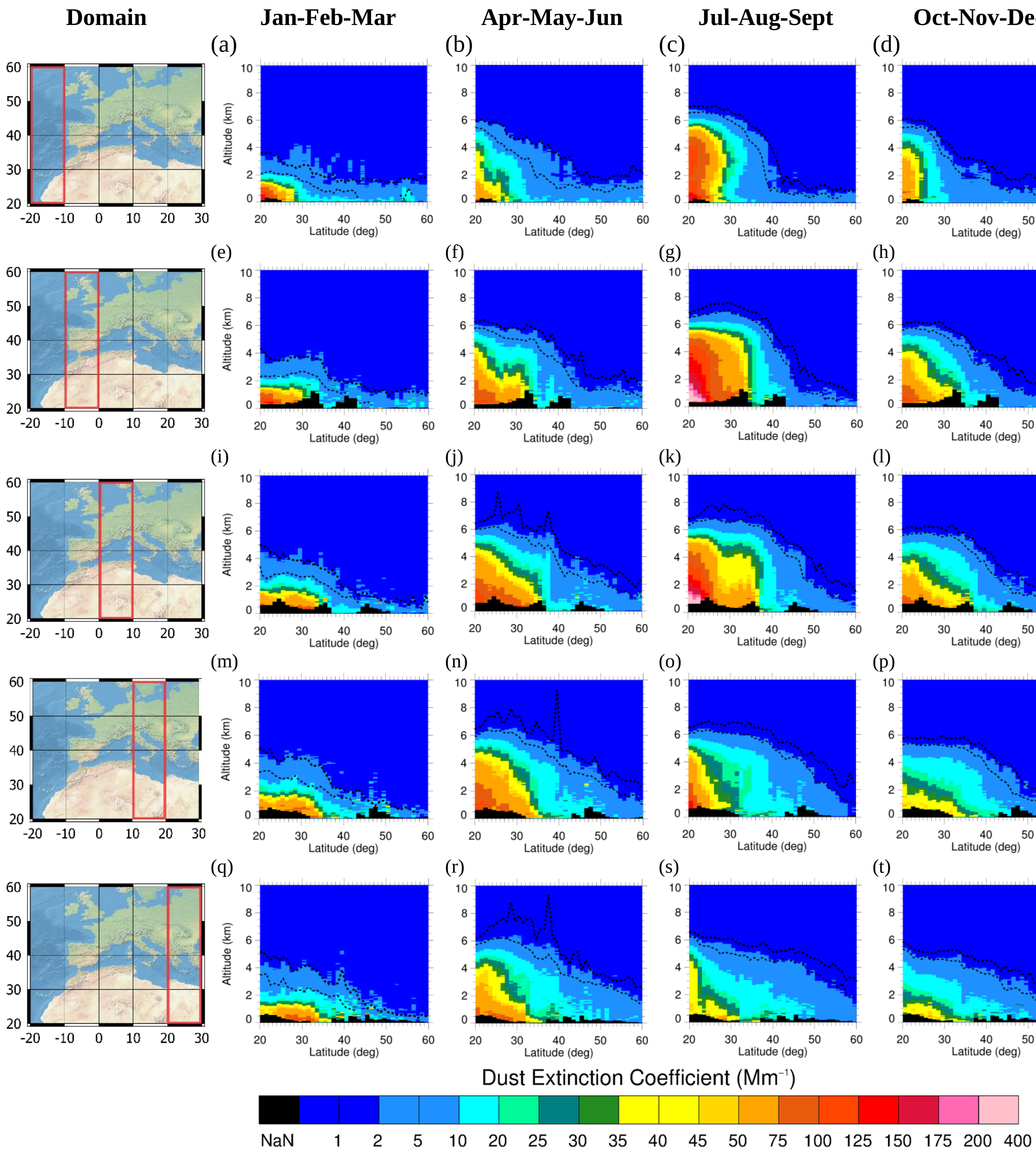

Domain
Jan-Feb-Mar
Apr-May-Jun
Jul-Aug-Sept
Oct-Nov-Dec
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
(p)
(q)
(r)
(s)
(t)
Altitude (km)
Latitude (deg)
Dust Extinction Coefficient (Mm⁻¹)
NaN 1 2 5 10 20 25 30 35 40 45 50 75 100 125 150 175 200 400

Fig.~~3~~4

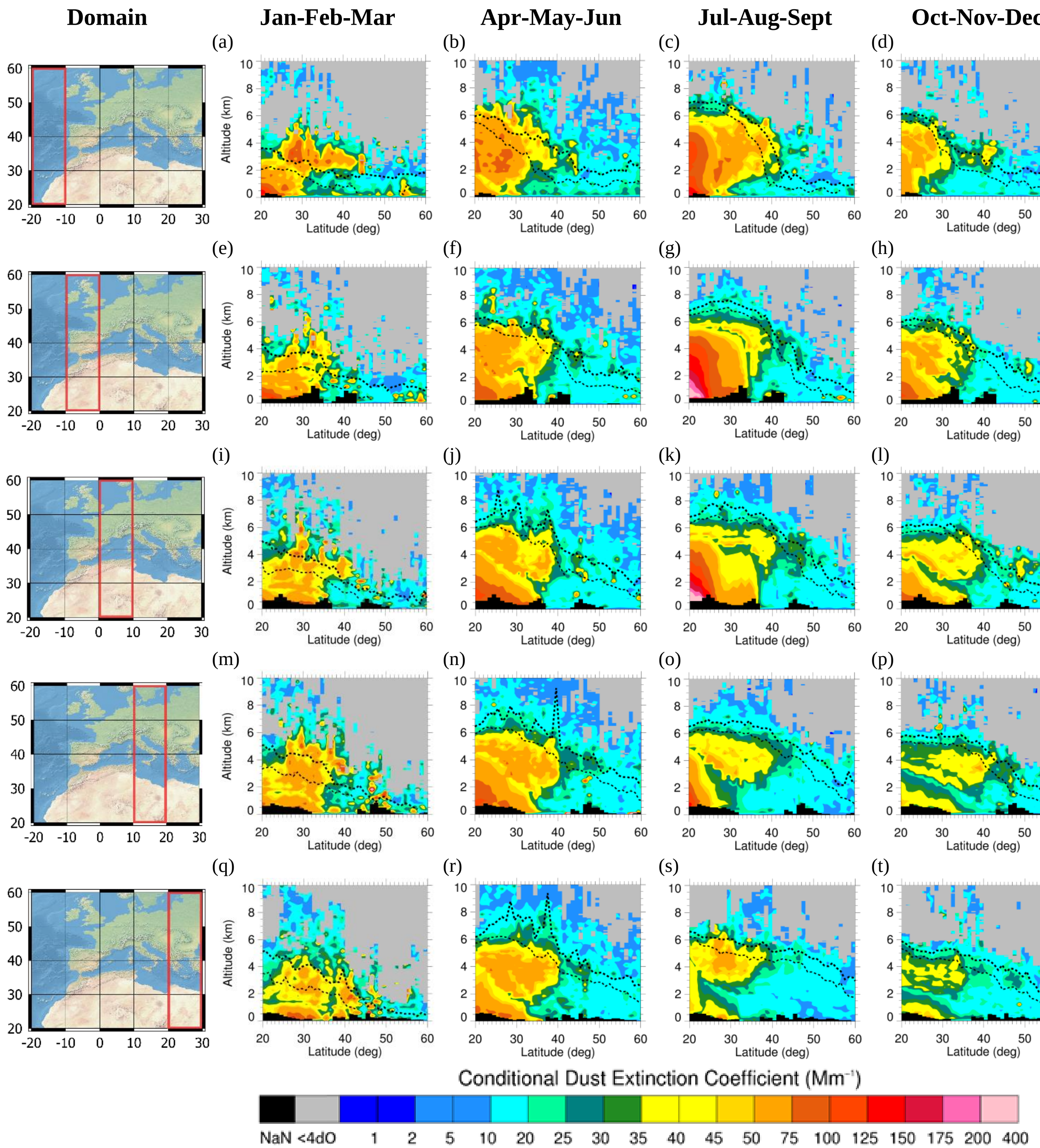
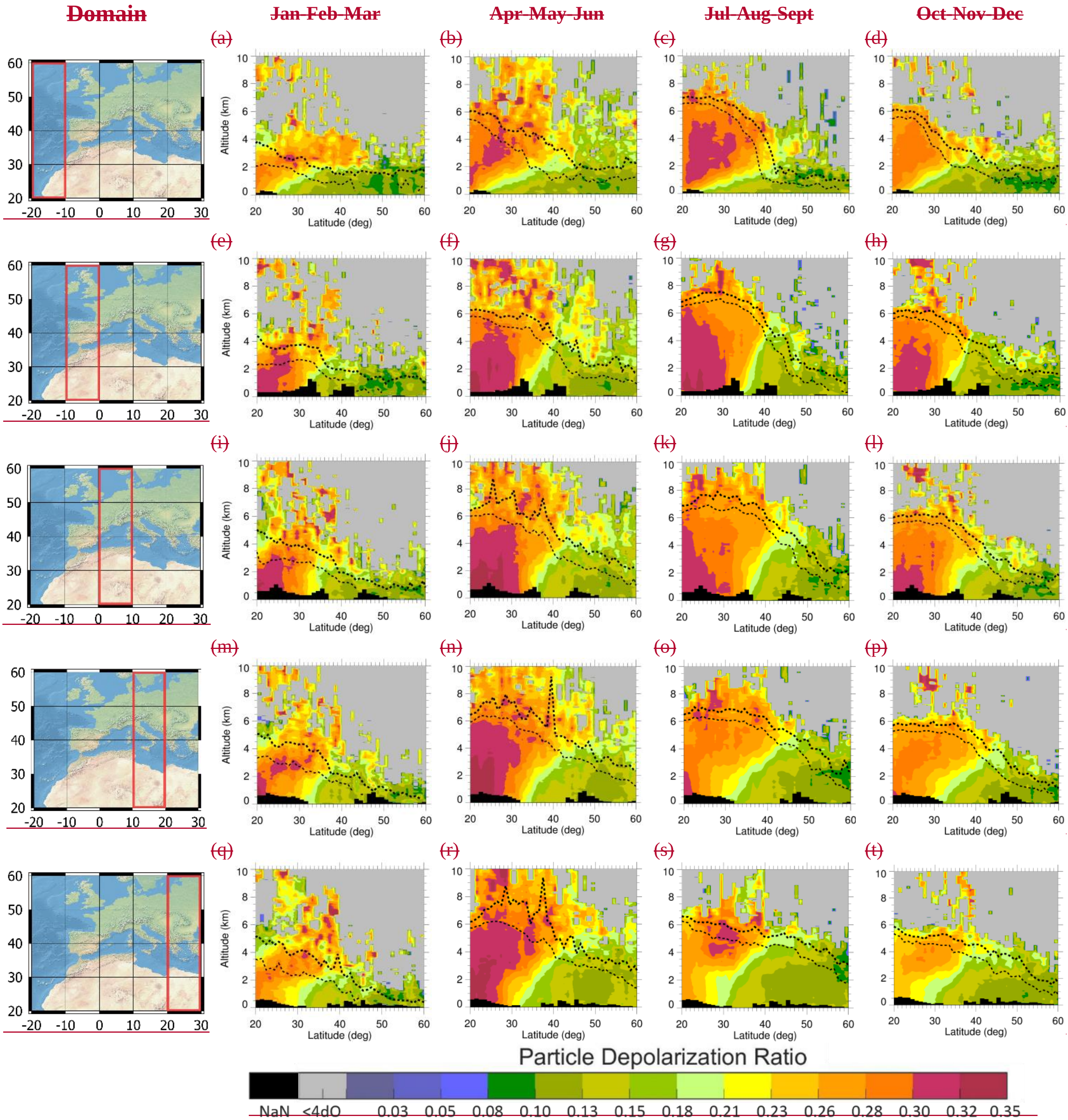

Domain
Jan-Feb-Mar
Apr-May-Jun
Jul-Aug-Sept
Oct-Nov-Dec
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
(p)
(q)
(r)
(s)
(t)
Altitude (km)
Latitude (deg)
Conditional Dust Extinction Coefficient (Mm⁻¹)
NaN <4dO 1 2 5 10 20 25 30 35 40 45 50 75 100 125 150 175 200 400

Fig. 45


Domain
Jan-Feb-Mar
Apr-May-Jun
Jul-Aug-Sept
Oct-Nov-Dec
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
(p)
(q)
(r)
(s)
(t)
Altitude (km)
Latitude (deg)
Particle Depolarization Ratio
NaN <4dO 0.03 0.05 0.08 0.10 0.13 0.15 0.18 0.21 0.23 0.26 0.28 0.30 0.32 0.35

~~Fig.5~~

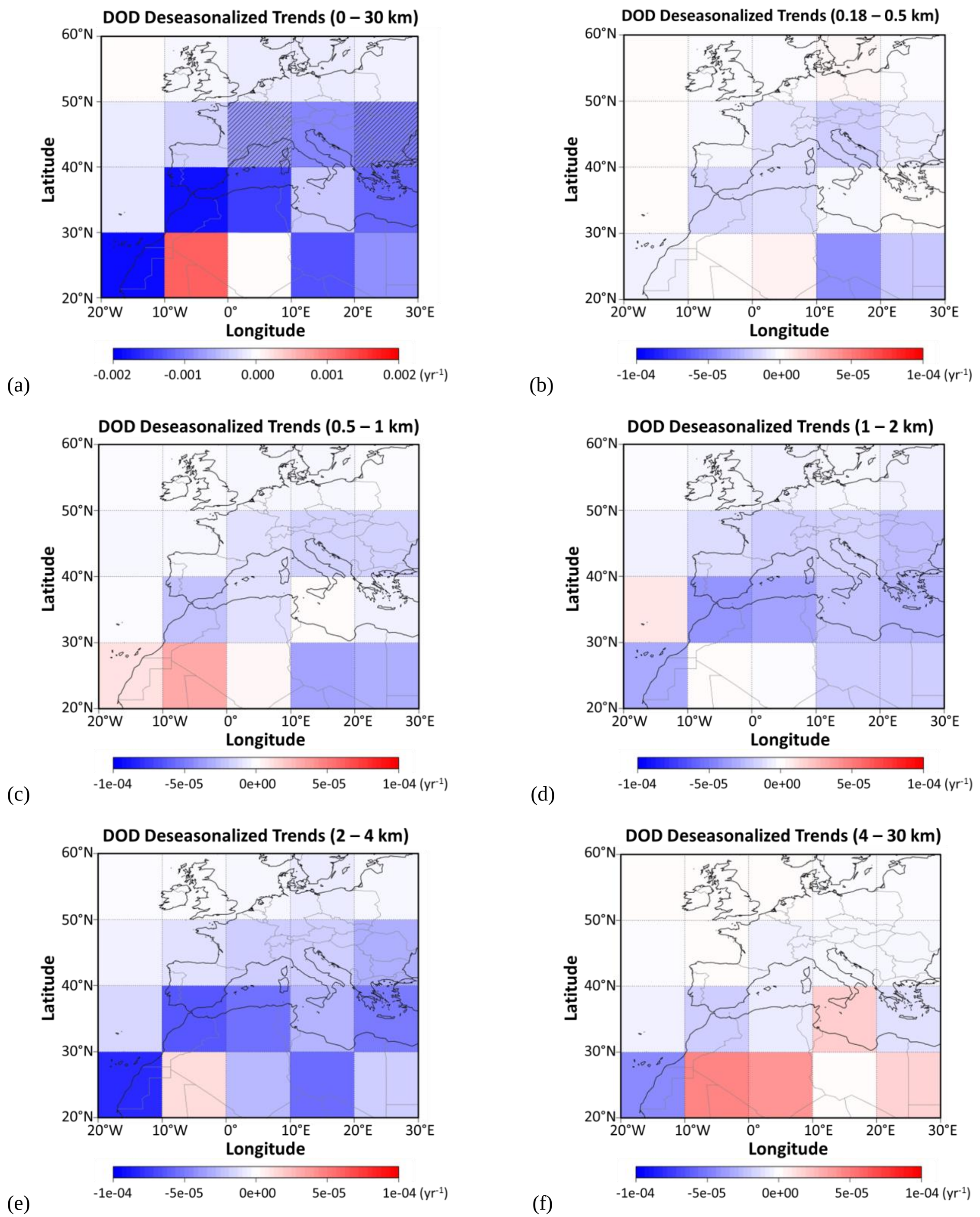

DOD Deseasonalized Trends (0 – 30 km)
DOD Deseasonalized Trends (0.18 – 0.5 km)
DOD Deseasonalized Trends (0.5 – 1 km)
DOD Deseasonalized Trends (1 – 2 km)
DOD Deseasonalized Trends (2 – 4 km)
DOD Deseasonalized Trends (4 – 30 km)
Latitude
Longitude
60°N
50°N
40°N
30°N
20°N
20°W
10°W
0°
10°E
20°E
30°E
-0.002
-0.001
0.000
0.001
0.002 (yr⁻¹)
-1e-04
-5e-05
0e+00
5e-05
1e-04 (yr⁻¹)
(a)
(b)
(c)
(d)
(e)
(f)

Fig.~~6~~ 6

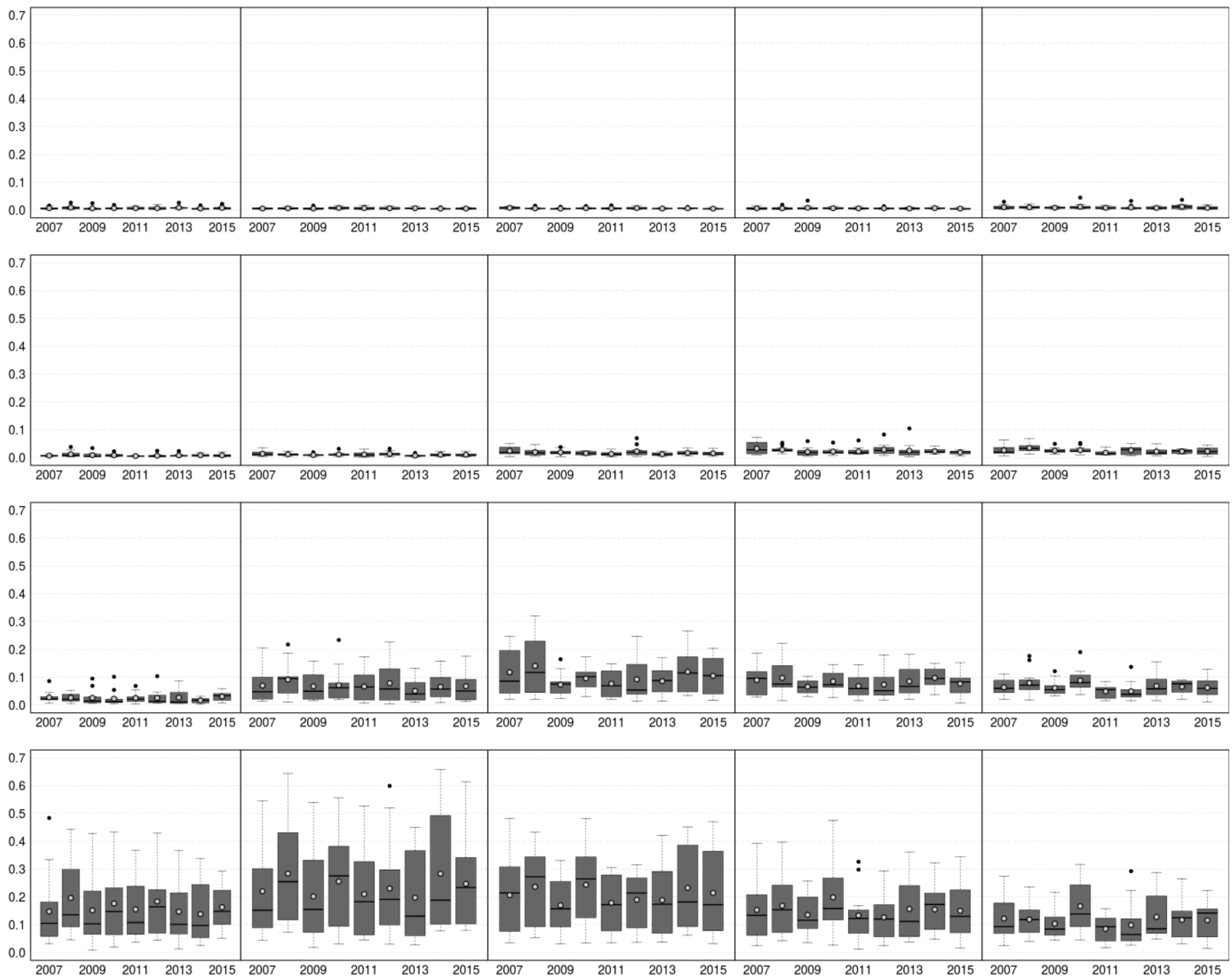


Fig. 7