Remote sensing and modeling analysis of the extreme dust storm hitting Middle East and Eastern Mediterranean in September 2015

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Abstract The extreme dust storm that affected Middle East and the Eastern Mediterranean in September 2015 resulted in record-breaking dust loads over Cyprus with aerosol optical depth exceeding 5.0 at 550 nm. We analyze this event using profiles from the European Aerosol Research Lidar Network (EARLINET), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), geostationary observations from the Meteosat Second Generation - Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI) and high resolution simulations with the Regional Atmospheric Modeling System (RAMS). The analysis reveals the main mechanisms that resulted in the generation and persistence of the dust cloud over Middle-East and Cyprus. A combination of meteorological and surface processes is found: (a) the development of a thermal low at the area of Syria that results in unstable atmospheric conditions and dust mobilization at this area; (b) the convective activity over North Iraq that triggers the formation of a westward moving haboob that merges with the previously elevated dust layer; and (c) the changes in land use due to war at the areas of North Iraq and Syria that enhances dust erodibility.

1. Introduction

A record dust storm affected the entire Middle East and Cyprus in September 2015. Remote sensing observations and in-situ measurements of Arabian dust from this episode during 7-11 September 2015 are presented by Mamouri et al. (2016) for the station of Limassol (34.7°N, 33°E). As reported in their article, the extreme amounts of dust over Middle East and East Mediterranean originate from the desert and arid areas of Syria and North Iraq. Triggered by this work, we analyze here the main processes that resulted in the mobilization of dust due to a combination of cyclonic flow and haboob formation.

Haboobs are local and mesoscale atmospheric density currents that mobilize huge amounts of dust and create a propagating dust wall extending up to 2-3 km in the troposphere (Knippertz et al., 2009; Solomos et al., 2012). These systems are well known by local populations at desert and arid areas worldwide due to their devastating impact in visibility and human health (e.g. Schepanski et al., 2009; Emmel et al., 2010). The responsible mechanism for haboob formation is the generation of a cold pool of ambient air due to evaporative cooling. The rain and ice condensates evaporate (or melt) as they fall through the warmer and unsaturated air and the absorption of latent heat from the phase changes leads in a vigor cooling of the surrounding air. When these convective outflow boundaries travel over bare soil and desert areas they result in the generation of a propagating dust wall. The scale of the processes that participate in the generation of such atmospheric density currents ranges from synoptic down to mesoscale and local. As a result, haboobs and their effects in weather and air-quality cannot be resolved by the coarse global model resolutions (Marsham et al., 2013). Moreover, haboobs usually generate over remote arid areas where no in-situ networks are present and inside dust-storm measurements can only be obtained during field campaign experiments (e.g. SAMUM 1 & 2, Ansmann et al., 2011; FENNEC, Ryder et al., 2015). Following these limitations, most of the efforts for the studying and forecasting of such intense dust episodes rely on passive and active remote sensing observations (e.g. MODIS, EARLINET, CALIPSO) and on high resolution modeling simulations. Assimilation of satellite derived Aerosol Optical Depth (AOD), has been shown to improve the dust forecasts in global models especially for the long range transport (Benedetti, et al., 2009); however this approach cannot be easily adopted for the description of haboobs. The reason is that the convective events and the associated wind gusts are not properly resolved at coarse model resolutions. As a result, assimilating the satellite AOD over an inaccurate

63 meteorological field does not improve the dust forecast.

64 A variety of studies on haboobs has been performed worldwide. Knippertz et al. (2009); Reinfried et

65 al. (2009); Solomos et al. (2012); Roberts and Knippertz (2014), analyzed the physical processes that

66 lead in severe haboob formation in Sahara as an aftermath of Atlas Mountains convective storms.

67 Bou Karam et al. (2008) showed the contribution of the east Atlantic monsoon flow and the

68 associated mesoscale convective systems (MCS) in dust elevation along the Sahel. Vukovic et al.

69 (2014) described the severe convective dust storm that hit Phoenix Arizona in July 2011. Asian

70 haboobs from the Taklimakan and Gobi deserts are described and simulated in Takemi, (1999,

71 2005). All these studies agree in the complexity and synergy between various physical processes at

72 multiple atmospheric scales that govern the generation and lifetime of these systems. Apart from

73 their devastating effects at local and near surface scales, such events may also contribute to the

74 free-troposphere dust burden in several ways: First, entrainment of dust particles in the free

75 troposphere takes place at the turbulent region of the density current head (Takemi, 2005; Solomos

76 et al., 2012); Second, they trigger secondary convective cells along their pathways that may evolve

77 to synoptic scale dust events and third, dust residuals remain aloft after the cold pool declines.

78 The current article is the second part (Part 2) in a series of articles on the September 2015

79 extraordinary dust storm in Middle East and Eastern Mediterranean. In Part 1, Mamouri et al.

80 (2016) present a detailed analysis of remote sensing and in-situ monitoring of the event over

81 Cyprus. The formation of similar events is not fully understood and we use this unique episode to

82 elucidate the mechanism of dust production in this understudied region. EARLINET measurements

83 along with CALIPSO and MSG observations are used to fine tune RAMS simulations and explain the

84 physical processes that resulted in this haboob-driven dust storm. We focus our analysis on the first

85 two days of the event (6 and 7 September 2015) when the extraordinary dust-storm was generated.

86 To the best of our knowledge this is the first detailed modeling and remote sensing study to

87 describe a Middle East haboob. The modeling and measurement techniques for the analysis are

88 presented in Section 2. Section 3 includes the model results, the remote sensing observations and

89 the investigation of the atmospheric processes that lead in the formation of the dust episode.

90 Conclusive remarks and discussion are presented in Section 4.

91

92 **2. Instruments and models.**

93

94 **2.1 Remote sensing observations**

95 **2.1.1. EARLINET**

96 The lidar station at Limassol (34.7° N, 33° E; 23 m above sea level, a.s.l.) is part of the European

97 Aerosol Research Lidar Network (EARLINET: Pappalardo et al., 2014). Details on the lidar station

98 equipment and the retrieval algorithms are given in Mamouri et al. (2016). Dust mass concentration

99 profiles are obtained from the dust optical properties following the methodology proposed by

100 Ansmann et al. (2012). For this case study we use a lidar ratio of 40 sr that is typical for Middle East

101 dust (Mamouri et al., 2013). The overall uncertainty in the estimated dust mass concentrations is

102 20-30%.

103

104 **2.1.2. CALIPSO**

105 CALIOP, the principal instrument on board the CALIPSO satellite is a standard dual-wavelength (532

106 and 1064 nm) backscatter lidar, operating a polarization channel at 532 nm (Winker et al., 2009).

107 CALIOP has been acquiring high-resolution profiles of the attenuated backscatter at 532 and 1064

108 nm along with polarized backscatter in the visible channel since 2006. After calibration and range

109 correction of the lidar backscatter signals (Level 1 CALIPSO product), cloud and aerosol layers are

110 identified and aerosol backscatter and extinction coefficient profiles at 532 and 1064 nm are

111 retrieved as part of the Level 2 CALIPSO product. The CALIPSO algorithms are described in detail in a

112 special issue of the Journal of Atmospheric and Oceanic Technology (e.g., Winker et al., 2009). In

113 this study, we utilize L2 version 3 Aerosol and Cloud profiles product at a horizontal resolution of 5

114 km analysis and vertical resolution of 60 m (in altitudes up to 8 km above sea level). In extreme

115 haboob events, where the optical signal is very high, it is possible for the algorithm to wrongly

116 attribute a dust layer as a cloud. In order to address this issue and fully understand the observed

117 scene we use collocated information derived from MSG-SEVIRI (see sect. 2.1.3). In the two CALIPSO

118 cases used here, MSG-SEVIRI RGB images confirmed that CALIPSO overpasses was cloud free, hence

119 we classify both aerosol and cloud categorized CALIPSO observations as aerosol. Moreover, both of

120 the cases have significantly high particle depolarization ratio values, which is a signature of pure

121 dust scenes. In order convert the dust extinction coefficient from CALIPSO into dust mass

122 concentration, we follow the methodology proposed by Ansmann et al. (2012) using the conversion

123   parameter of desert dust that is proposed in Mamouri and Ansmann (2017).

124

125   **2.1.3. MSG-SEVIRI**

126   The Meteosat dust RGB composite is produced from a combination between three MSG channels:

127   IR12.0-IR10.8 (red), IR10.8-IR8.7 (green) and IR10.8 (blue). This product is provided in hourly

128   intervals by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)

129   and aims in the monitoring of dust transport. Dust in these RGB images appears in pink or magenta

130   colors while green-blue and red-brown colors are reserved for land and clouds respectively (Lensky

131   and Rosenfeld, 2008).

132

133   **2.2 Modeling simulations**

134   **2.2.1 RAMS-ICLAMS model**

135   For the simulations used in this study we adopt the online coupled atmospheric and air quality

136   modeling system RAMS-ICLAMS (Pielke et al., 1992; Meyers et al., 1997; Cotton et al., 2003;

137   Solomos et al., 2011). The Integrated Community Limited Area Modeling System (ICLAMS) is an

138   enhanced version of RAMS6.0 and it has been developed by the Atmospheric Modeling and

139   Weather Forecasting Group at the University of Athens, Greece. The model is set up in a two-way

140   nesting configuration. The external domain grid space is set at 12×12 km and the grid space of the

141   inner domain is set at 4×4 km. A higher resolution (cloud resolving) grid at 2×2 km is nested over the

142   haboob generation area at Syria-Iraq-Iran-Turkey borders. The locations of the model domains are

143   shown in Figure 1b. The vertical structure of the model consists of 50 terrain following levels

144   stretching from the surface up to 18 km. The dust production scheme follows the saltation and

145   bombardment approach (Marticorena and Bergametti 1995; Spyrou et al., 2010). Wet and dry

146   deposition of dust is formulated following Seinfeld and Pandis 1998. Mineral dust is represented

147   with a transport mode of eight radii bins namely 0.15, 0.25, 0.45, 0.78, 1.3, 2.2, 3.8 and 7.1 μm. Sea

148   salt aerosol is also parameterized following Monahan et al., 1986; Zhang et al., 2005; Leeuw et al.,

149   2000 and Gong et al., 2002, 2003 and it is represented with an accumulated and a coarse mode at

150   0.18 μm and 1.425 μm in radius respectively. Dust and sea salt particles interact with the radiative

151   transfer code of the model (Rapid Radiative Transfer Model (RRTM), Mlawer et al., 1997; Iacono et

152   al., 2000) for the computation of heating rate fluxes. The formation of cloud condensation nuclei

153   (CCN) and ice nuclei (IN) from dust and sea salt particles is also included in the model based on the

154   schemes of Fountoukis and Nenes, 2005 and Barahona and Nenes 2009. Initial and boundary

155   conditions are from the NCEP final analysis dataset (FNL at 1°×1° resolution) and the sea surface

156   temperature is the NCEP operational SST at 0.5°×0.5°. The convective parameterization scheme of

157   Kain and Fritsch, 1993 (KF) is activated for the two coarser grids. Assimilation of radiosonde data

158   from the airports of Adana (36.98°N, 35.35°E), Bet Dagan (32.00°N, 34.81°E), Diyarbakir (37.54°N,

159   40.12°E), Mafraq (32.36°N, 36.25°E) and Nicosia (35.10°N, 33.30°E) is also activated to fine tune the

160   simulations. A series of sensitivity runs with various model configurations (different physical

161   schemes, assimilation parameters and domain structures) is performed until we conclude to the

162   optimum setup for the specific simulation.

163

164   **2.2.2 Land use changes and activation of dust sources**

165   An accurate representation of dust sources in the region is crucial for understanding this complex

166   dust event, but this is hampered by recent land cover changes in the region. The original land use

167   database of the model is the USGS Data Base Version 2 which is obtained from 1-km AVHRR data

168   (Advanced Very High Resolution Radiometer) spanning April 1992 through March 1993. However,

169   complex interactions of drier climate (Notaro et al., 2015; Cook et al., 2016), transboundary water

170   managements (Voss et al. 2013), and prolonged conflict (Jaafar and Woertz, 2016) have led to

171   change of land use types that are no longer reflected at the model and this could have a large

172   impact on dust production. The comparison of Landsat 8 natural color and NDVI imagery between

173   2013 and 2015 (Figure 2) reveals large areas of uncultivated fields in regions of contested boarders

174   and exposed river and lake-bed sediments especially around the Euphrates river, all of which are

175   known to be very efficient dust sources (Prospero et al, 2002; Ginoux et al., 2012). In order to get

176   most accurate representation of dust sources for the specific event we use 1km monthly

177   Normalized Difference Vegetation Index (NDVI) from MODIS (Didan K., 2015) to characterize land

178   use type in the region of interest. Specifically, we consider regions with NDVI values from 0 to 0.1 to

179   correspond to bare soil and consequently efficient dust sources (DeFries et al., 1994). The updated

180   land cover dataset is used for all results shown in this study. Results from simulations using the

181   older database are only shown in Figure 11 for comparison.

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185 **3. Results**

186 **3.1 Meteorological conditions**

187 The main driving force for the generation of this extreme dust episode is the combination between

188 two distinct meteorological features in the greater area: (i) establishment of a thermal low over the

189 bare-soil areas of Syria and (ii) convective outflow boundaries at the mountains of Iraq and Syria.

190 These processes are analyzed in the following sections using modeling results and remote sensing

191 observations.

192 **3.1.1 Development of a low pressure system over Syria on 6 September 2015**

193 As seen at the outer model grid in Figure 1a, the passage of a trough is evident over Turkey on 6

194 September 2015, 00:00 UTC. The low pressure center at 500mb is found at 5840 m over the east

195 bank of Black Sea. During the same day, radiative warming of the bare soil surface results in very

196 hot soil temperatures exceeding 50 °C in Syria and Iraq. This combination of cold air aloft with low

197 level warming, leads in the formation of a thermal low pressure system over Syria. Another

198 parameter that plays important role for the process of dust source activation is the difference

199 between surface temperature (T_{Surf}) and air temperature at 2m (T_{2m}). Findings from earlier field

200 experiments (i.e. SAMUM) show that such a difference of 17°C-20°C facilitates the uplift of

201 convective dust plumes (Ansmann et al., 2009). As seen in Figure 1b, the modeled T_{Surf}-T_{2m}

202 difference at 10:00 UTC exceeds 17°C over extended bare soil areas in Syria. This temperature

203 gradient further explains the effectiveness of dust production at these areas. The pressure system

204 and the associated cyclonic flow persist during the entire day of 6th September 2015 and result in

205 the mobilization of dust in the area. The low pressure system is evident by the 850 mb geopotential

206 height contours in Figure 3a, reaching a minimum of 1490 m at 08:00 UTC, 6 September 2015. Dust

207 uptake is mostly evident at the outer parts of the cyclone where surface wind speed exceeds 7 m s^{-1}

208 almost during the entire day and T_{Surf}-T_{2m} obtains maximum values. The elevated particles are

209 quickly distributed inside the system and a distinct cylindrical dust cloud is soon formed.

210 Recirculation of the elevated dust particles inside the closed cyclonic flow results in extreme AOT

211 values exceeding 15 at specific areas as seen in Figure 3a. The formation of this dense dust plume is

212 also evident in the MSG-SEVIRI satellite dust RGB image in Figure 3b. Pink and purple colors in this

213 image indicate dust while brown and red colors indicate clouds. As seen in Figure 4, convergence of

214 low level flow along the Mediterranean coastline during the morning hours on September 6th,

215 results in local convective activity at the area of Lebanon Mountains and in local disturbance of the

216   mesoscale wind field. A SE flow is established, and this flow is responsible for the transport of dust

217   from Lebanon towards Cyprus that is evident at the satellite and modeling images on 7 September

218   2015, 00:00 UTC (Figure 5). This cut-off plume (plume_1) travels in the lower troposphere above

219   the marine boundary layer and it was observed at 1.5 km above Limassol at 19:00 UTC on

220   September 7th as reported by Mamouri et al., 2016. The faster propagating haboob plume

221   (plume_2) also was detected at 2.0-3.5 km over Cyprus at 19:00 UTC. The extreme AOT values (>10)

222   that are seen in Figure 5a over Syria result from the overlapping of cyclone-driven and haboob-

223   driven dust over this area. In the model, approaching of the haboob front in Syria is accompanied

224   also by cloud formation as seen by the 70% cloud-cover contours in Figure 5a; however these clouds

225   are not evident in the satellite image (Figure 5b). The more elevated (cyclone-driven) dust in Figure

226   5b is shown in pink (plume_1 over the sea and plume_3 over North Syria and South Turkey have the

227   same origin) and the near surface dust (haboob) is shown with a darker purple color (plume_2).

228

3.1.2. Convection and haboob generation on 6 and 7 September 2015

230   At 13:00 UTC on 6th of September a northward low level flow is evident over N. Iraq and N. Syria

231   (Figure 6a). This relatively unstable air mass is characterized by increased equivalent potential

232   temperature (theta_e) reaching up to 508 K. This flow is associated with a westerly shift of the

233   Somalian Low Level Jet (SLLJ). The SLLJ is part of the West India Monsoon circulation and as shown

234   in Figure 6b it is characterized by strong SW winds blowing from the Somalia highlands towards

235   West India. This low level flow steers towards the west along the coastal mountains of Yemen and

236   Oman and results in SE winds transferring moisture from the Arabian Sea towards the inlands of the

237   Arabian Peninsula. Mechanical elevation of this relatively unstable air as it approaches Mt. Sinjar in

238   N. Iraq (Figure 6a) triggers convection at this area. A crucial parameter that determines the

239   formation of a cold pool is the temperature difference between rain droplets and the ambient air.

240   As seen in Figure 7a, the absolute difference between rain droplets temperature and ambient air

241   temperature in the model reaches a maximum of 22 °C at this area. This temperature gradient

242   results in a faster evaporation rate of the rain droplets as they fall through the unsaturated air and

243   in the formation of a cold pool at the area of North Iraq. Wind speed inside the cold pool ranges

244   from 10 up to 20 ms^{-1} (Figure 7b). This cold pool moves towards the North and triggers the

245   generation of secondary convective cells at the mountainous areas along Iran-Iraq-Turkey

246   borderline. At 20:00 UTC, a series of convective outflows converges in an organized SE propagating

247   density current that is evident in the model over N. Iraq and N. Syria (Figure 8a). This system is

248   characterized by wind speeds higher than 6 m s^{-1} and results in activation of dust sources and near

249   surface concentrations largely exceeding 10000 μg m^{-3} (Figure 8b). However, the corresponding

250   SEVIRI image (Figure 8c) indicates that by this time the haboob has already penetrated about 200

251   km inside Syria which is not reproduced by the model. This latency between satellite and modeled

252   haboob fronts is an indication that the convective downdrafts were in fact even stronger.

253

254   **3.2 Dust cloud properties and comparison with observations**

255   **3.2.1. Vertical dust structure**

256   The dust layer structure as it propagates towards the Mediterranean is captured by two CALIPSO

257   overpasses at 23:33 UTC, 6 September 2015 (Figure 9) and at 10:35 UTC, 7 September 2015 (Figure

258   10). Collocated model cross sections of dust and MSG-SEVIRI dust images are also presented in

259   Figures 8 and 9. All heights in satellite and model profiles refer to heights above surface. At the first

260   overpass (Figure 9), the south part of the dust layer (31°N-34°N) is detected up to 2-3 km and

261   originates from the cyclonic flow over Syria. Dust concentrations are estimated from CALIPSO

262   backscatter and as seen in Figure 9b they reach up to 5000 μg m^{-3} close to the surface between

263   31°N-34°N and higher than 6000 μg m^{-3} in the first 500 m. Similar structure and dust concentrations

264   are also found by the model (Figure 9c). The northern part of the overpass (35°N-38°N) detects also

265   elevated dust due to cyclonic activity between 2.5-4.5 km and concentrations up to 1000-2000 μg

266   m^{-3} are evident at this area from CALIPSO. The model overpredicts dust at this area with simulated

267   concentrations reaching up to 5000 μg m^{-3}. These elevated layers are shown with pink colors in

268   Figure 9a. Low level dust (purple colors in SEVIRI images) is also evident in this area due to the

269   propagating haboob and CALIPSO detects this two-layer structure with a clear separation at 2 km.

270   The model also reproduces the uplift of dust at 35°N where the two systems (cyclone and haboob)

271   merge. The modeled concentration inside the haboob reaches extraordinary values exceeding

272   10000 μg m^{-3}. Due to the severity of the event, the CALIPSO lidar signal is totally attenuated bellow

273   ~1 km (dark blue color), in the area between 35°N-37°N. For that reason the information from the

274   satellite is limited there in the highest 500m of the propagated haboob, implying also the existence

275   of much higher values close to the surface.

276   The second overpass at 7 September 10:35 UTC is actually behind or at the tail of the propagating

277   dust storm (Figure 10a). The thin dust layer that is detected by CALIPSO between 30°N-32°N reaches

278 up to 2 km and maximum dust concentrations of up to 2000-3000 µg m^{-3} are calculated mostly close

279 to the surface (Figure 10b). Extreme dust concentrations are also found in both satellite and model

280 plots between 34°N-36°N at the tail of the propagating system. Dust values at this area are so high

281 that CALIPSO observation suffers again from total attenuation of the lidar signal after penetrating

282 the first 1000 m and extraordinary concentrations of up to 20000 µg m^{-3} are found in the lower

283 model levels (up to 1.5 km). Similar values are observed from CALIPSO in the edge of the haboob

284 (33.5°N-34°N) where the signal is strong enough to provide valuable information. The elevated

285 layers (2-4 km) between 36°N-38°N at both CALIPSO and model profiles are dust residuals over the

286 mountains of Turkey. An elevated dust layer of up to 600 µg m^{-3} is also found south of 35°N in the

287 model at heights between 3-4 km. Due to the aforementioned latency between the true and

288 modeled propagation speeds, the model cross-section is closer to the core of the system hence this

289 layer consists of modeled cyclone uplifted dust that in fact is already west of the CALIPSO track.

290

291 3.2.2. Dust load over Cyprus

292 The observed structure and amounts of dust arriving in Cyprus is described in detail by Mamouri et

293 al. (2016). The arrival of the dust plumes at Limassol in Cyprus is evident in Figure 11. A double layer

294 structure is detected by the lidar at 7 September 19:00 UTC. The relatively shallow dust layer that is

295 found between 0.8-1.7 km with a maximum peak at 2000 µg m^{-3}, comes from the detached dust air

296 mass traveling off the coast of Libanon as described in Section 3.1.1. The model reproduces

297 correctly the height of this layer but the maximum concentration is underestimated by almost 50 %.

298 The upper layer that is detected between 1.8-3.6 km originates from the north part of the fast

299 propagating haboob that catches up with the "Lebanon" dust over Cyprus. The location and dust

300 concentrations of this layer are adequately reproduced by the model. The total modeled dust load

301 is similar to the observed (lidar) dust load but the vertical distribution of dust in two distinct layers

302 is not so clearly reproduced. Model results using the old vegetation database are also shown in

303 Figure 11. As seen by the dashed line in this plot, this simulation failed to reproduce the strength of

304 the event and the maximum concentration is 400 µg m^{-3} at about 0.7 km height. On the 8th of

305 September the lidar system could not operate due to the extraordinary dust load. The mean MODIS

306 derived AOT on this day varied between 1.5-5 over five sites in Cyprus (Pafos, Limassol, Larnaca,

307 Nicosia, Rizokarpaso), (Mamouri et al., 2016). Given the fact that the maximum retrievable MODIS

308 AOT is 5, these values are most probably an underestimation of the true AOT. The distribution of

309   modeled AOT during 00:00 UTC-15:00 UTC on the 8th of September is shown in Figure12; the dust

310   plume approaches Cyprus from the South and the orographic effect of Mt. Troodos results in an

311   inhomogeneous distribution of dustload over the island, which explains the AOT variability between

312   the sites. The modeled AOT values over the Middle East inland exceed 10 as shown also by the

313   sharp gradient towards the eastern part of Figure 12 plots. However the extreme dust storm

314   affecting Cyprus during the 8th of September is the result of a plume that approaches the island

315   from the south. This dust layer is evident between 1.5-3.5 km in the vertical cross-sections of model

316   dust concentration at 00:00 UTC and 03:00 UTC in Figure 13. Downward mixing of dust as this air

317   mass approaches the topographic barrier of Troodos mountain increases the near-surface

318   concentrations at the southern sites especially during local morning and noon hours (06:00 UTC,

319   09:00 UTC). In the afternoon hours (12:00 UTC, 15:00 UTC), the development of upward motions

320   over Mt. Troodos separates the dust flow over Cyprus into two distinct cells (a south and a north

321   one) and at this time increased concentrations are found over the northern sites of the island. The

322   maximum simulated concentrations are up to 4000 $\mu g\ m^{-3}$ aloft and about 1000 $\mu g\ m^{-3}$ close to the

323   surface. Taking into account the complexity of the situation, the spatiotemporal evolution of the

324   episode seems to be correctly explained by the model but the extreme values of 8000-10000 mg m^{-3}

325   that are reported by Mamouri et al. (2016) are not reproduced. This discrepancy can be attributed

326   to a variety of reasons related to both dust and atmospheric properties that are not properly

327   resolved even at this fine model scale (e.g. more intense downward mixing or increased emissions

328   from the sources). The modeled versus observed maximum AOT values for the five sites are also

329   shown in Table 1. The model reproduces the higher AOTs at the most southern sites (Limassol and

330   Pafos) compared to the central and north sites. Following the previous discussion about the already

331   underestimated MODIS AOT it seems that the model reproduces the distribution of dust over

332   Cyprus however with an overall underestimation of more than 2. A possible explanation could be

333   also that the dry river beds of Tigris and Euphrates as well as several dust sources over Syria and

334   North Iraq provide even more erodible sediments than those assumed by the model hence the

335   discrepancies in dust concentrations.

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339

340   Table 1. Maximum MODIS and RAMS AOT over Cyprus, 8 September 2015

	Pafos	Limassol	Larnaca	Nicosia	Rizokarpaso
MODIS$_{AOT}$	3.5	5.0	5.0	2.0	5.0
RAMS$_{AOT}$	3.5	4.0	3.0	3.0	3.0

341

342

343   **4. Discussion and Conclusions**

344   A combination of meteorological and landuse conditions resulted in the formation of an

345   unprecedented dust episode over Middle East and East Mediterranean during 6-11 September

346   2015. This event is unique due to the coincidence of various atmospheric phenomena related with

347   the generation of turbulence and dust production. Interpretation and analysis of remote sensing

348   data (EARLINET, CALIPSO, MSG-SEVIRI) and modeling simulations (RAMS-ICLAMS) reveals the main

349   reasons that led in the uplift and persistence of the dust layers. The major processes affecting the

350   generation of the dust storm are found to be:

351   1. The formation of a strong thermal low over Syria that lifted dust up to 4 km.

352   2. The intrusion of a moist and unstable air mass from the Arabian Sea that triggered
353   convective activity over Iraq-Iran-Syria-Turkey borderline.

354   3. The generated outflow boundaries that led in dust deflation and formed a westward
355   propagating haboob merging with the previously elevated dust over Syria.

356   4. The efficiency of Middle East dust sources is increased as an aftermath of war and the
357   related changes in land use.

358   As reported by Mamouri et al. (2016), almost all operational dust models failed to forecast this

359   event. RAMS-ICLAMS in this study is not used in forecasting mode but rather as a tool for the a-

360   posteriori analysis and explanation of the event. This means that the configuration of several model

361   parameters such as the nested grid structure, convective parameterization schemes, dust source

362   strength etc. is guided by the available observations. In this context, most observed processes are

363   successfully described by the model and the various physical mechanisms that took place during the

364   event are explained. However, certain inaccuracies in the quantification of atmospheric variables

365   and spatiotemporal deviations in the description of convection and other physical processes can still

366   significantly decrease the model skill especially regarding the quantification of dust mass profiles.

367   The analysis presented here raises considerations regarding the forecast skills of the atmospheric

368   dust models, since even though such extreme episodes are very seldom they still represent the

369   most threatening dust hazards. The long range transport and the general circulation of dust in the

370   atmosphere are nowadays adequately forecasted by most global models but convectively driven

371   episodes cannot be resolved at synoptic and mesoscale resolutions. Moreover, a recent study by

372   Pope et al., 2016 suggests that unresolved haboobs may be responsible for up to 30% of the total

373   atmospheric dust and such considerations raise questions on the current status of early warning

374   systems for dust episodes. It is probably obvious that such a system cannot rely exclusively on

375   modeling simulations. As shown at the present study, the complexity of these events makes their

376   forecast very challenging and even at convection permitting resolutions, it is possible that a certain

377   model configuration could successfully reproduce a specific event but not all similar events.

378   Moreover, such high resolution grid-space can only be applied over limited areas due to restrictions

379   in computational power.

380   Remote sensing observations can play an important role for the provision of more accurate dust

381   forecasts. Engagement of geostationary satellite observations (MSG, Sentinel-4) and CALIPSO

382   profiles in forecasting activities could improve the forecasting skill either by the direct assimilation

383   of satellite data in dust models or by issuing human-assisted early warnings. Expansion of a lidar

384   network close to dust source areas (e.g. Sahara, Middle East) will also complement model activities

385   through the provision of ground truth observations for the vertical profile of dust plumes.

386   Additionally, the activation of synchronous observations from the EARLINET network following a

387   dust forecast notice will allow a closer investigation of the physical processes that drive these

388   events

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391

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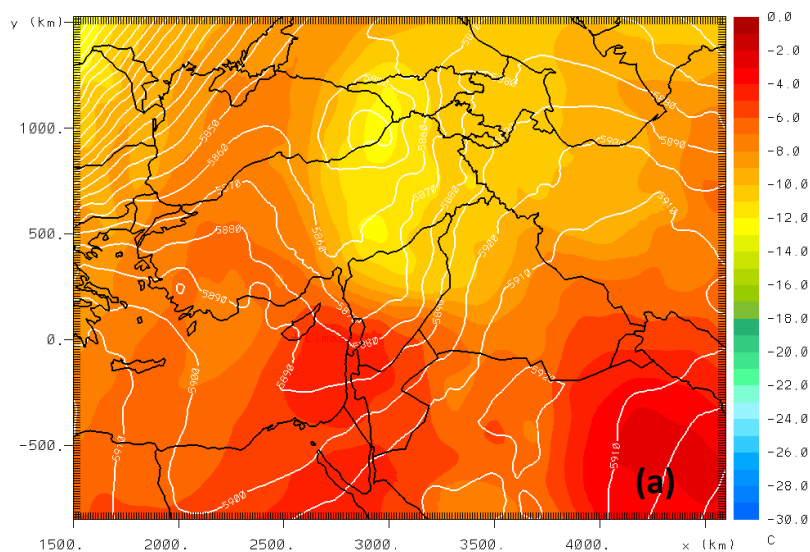
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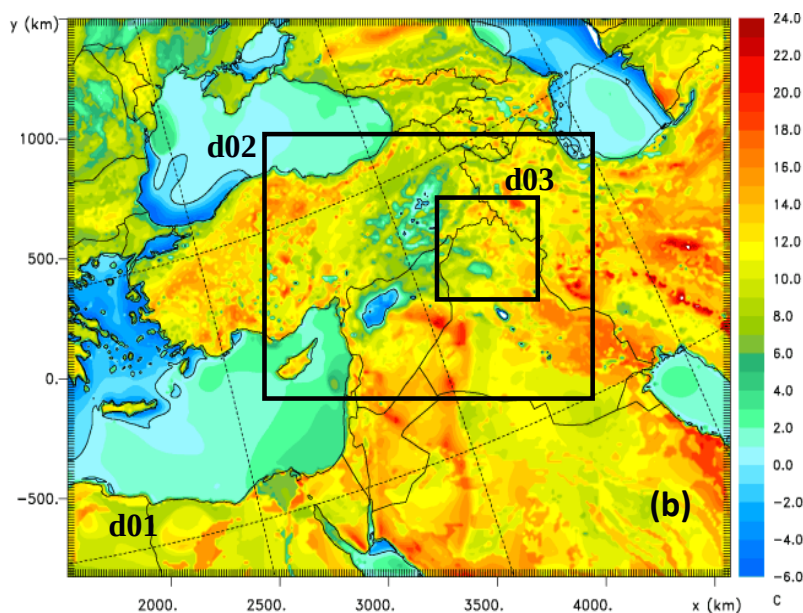
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553   Figure 1. a) Model geopotential height contours (every 10 m) and temperature (color scale in °C) at

554   500mb, 6 September 2015, 00:00 UTC; b) Difference (°C) between model soil temperature and

555   model temperature at 2m, 10:00 UTC, 6 September 2015. Black rectangulars indicate the location of

556   the nested model domains (d01:12×12 km, d02:4×4 km, d03:2×2 km).

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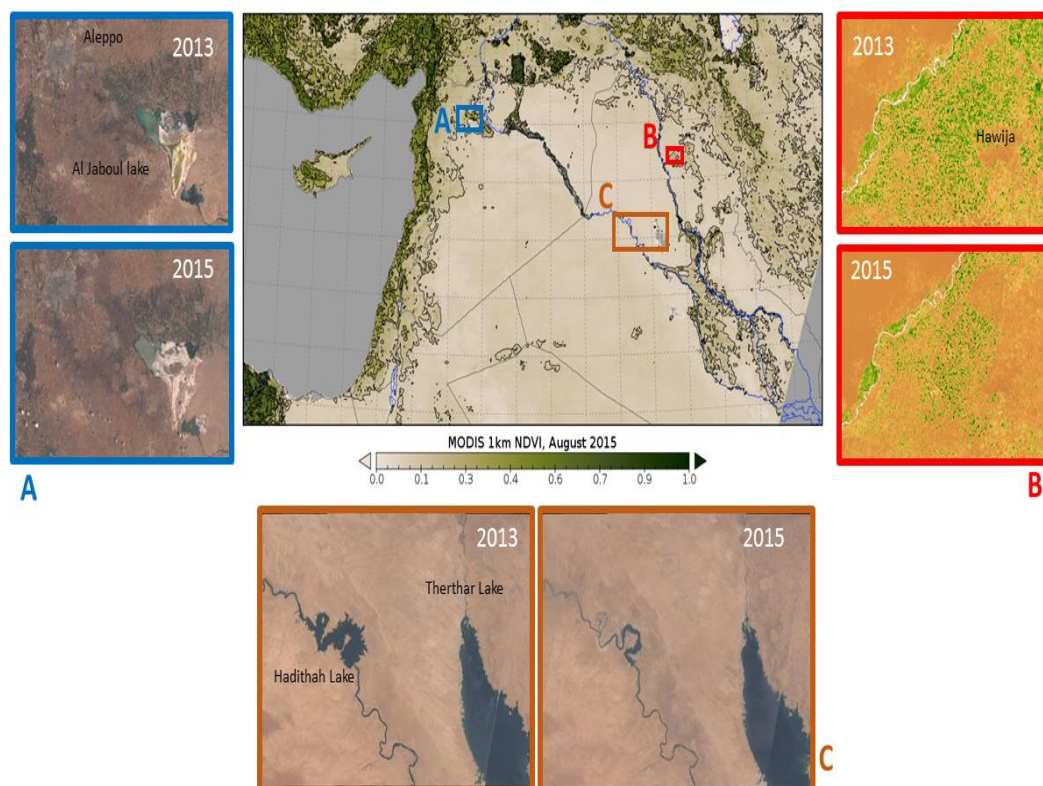
Figure 2. (central panel) MODIS NDVI observations for August 2015 were used to identify regions of bare soil that can be sources of dust aerosols. The contour lines correspond to the major ticks of the color scale. Large regions of wester Syria and Iraq have NDVI values from 0 to 0.1. The three subpanels show examples of land type change between summer 2013 and summer 2015. (Subpanel A) Landsat 8 natural color images of Aleppo region, Syria shows changes of cultivation patterns and drying of nearby Al Jaboul lake (e.g. the bright areas of the Al Jaboul Lake - dry parts of the lake - increased from 2013 to 2015); (Subpanel B) Landsat 8 NDVI index images in the region of Hawija, Kirkuk Province, Iraq reveal that large areas remained uncultivated in 2015 (e.g. the 2013 map shows many more green spots - agriculturally used areas - than the 2015 map); (Subpanel C) Landsat 8 natural color images showing diminishing area of Haditah Lake on the Euphrates river and the drying up of the Therthar canal and lake.

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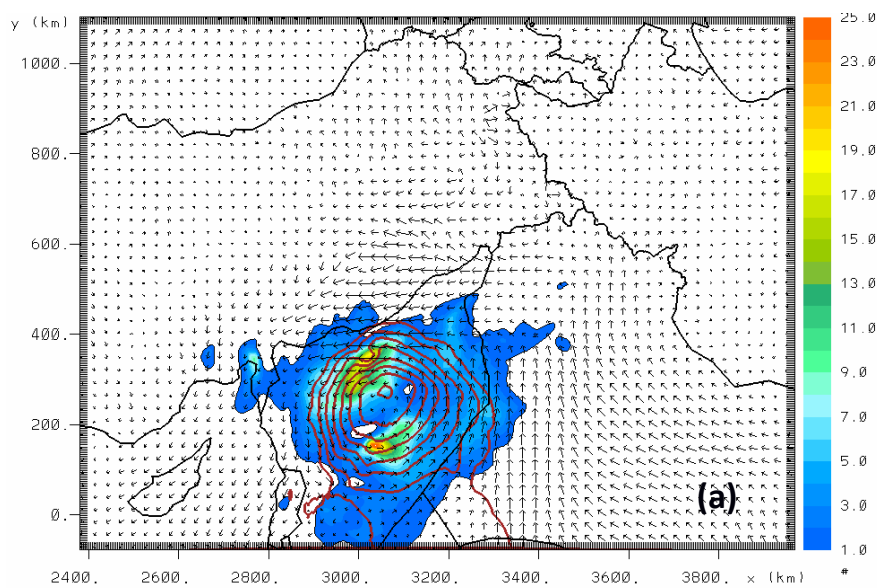
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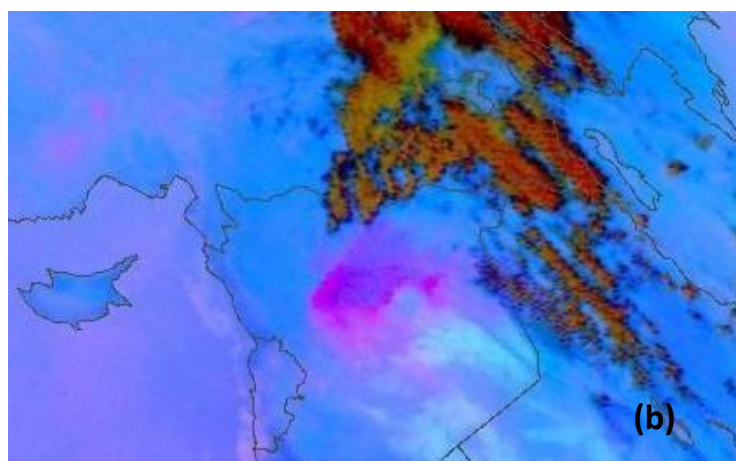
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575   Figure 3. a) Model AOD (color scale) , geopotential height at 850 mb (red contours from 1490 to

576   1505 m every 2.5 m) and wind vectors at 850mb ; b) MSG SEVIRI dust RGB at 08:00 UTC, 6

577   September 2015

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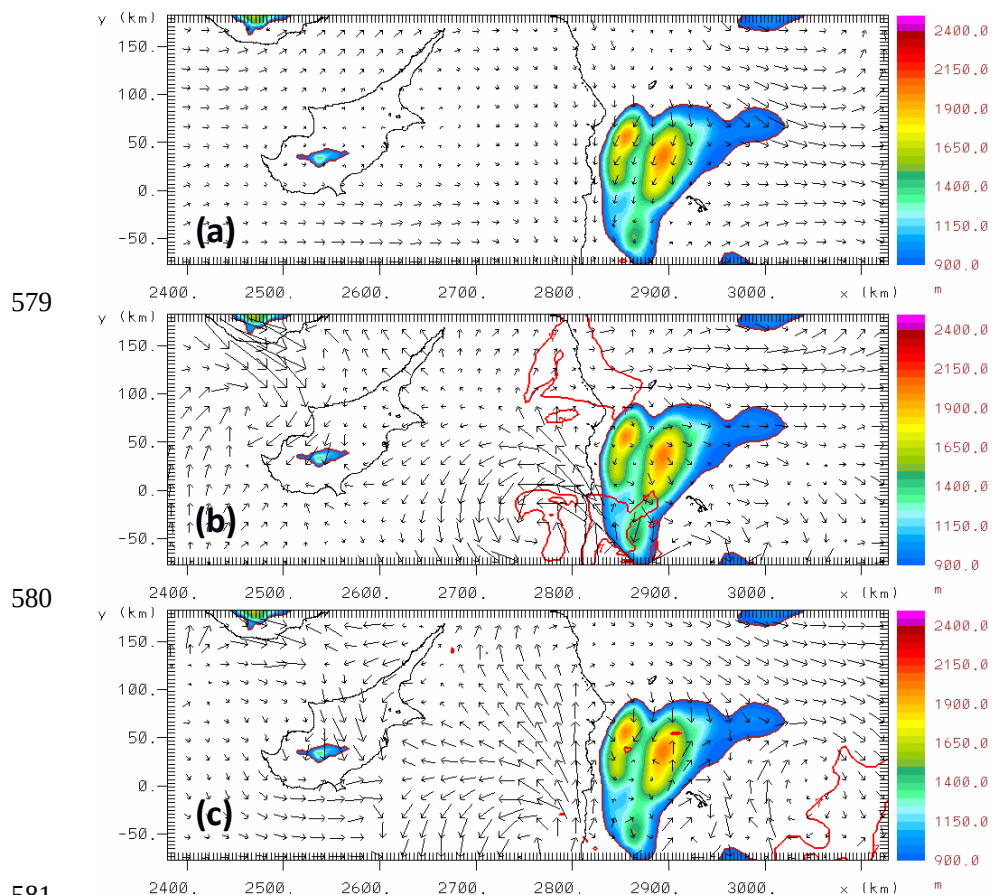
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582 Figure 4. Model topography (color scale), wind vectors at the first model layer (50 m) and cloud
583 fraction > 70% (red contour), zoom from the second model grid, 6 September 2015, 00:00, 06:00,
584 12:00 UTC.
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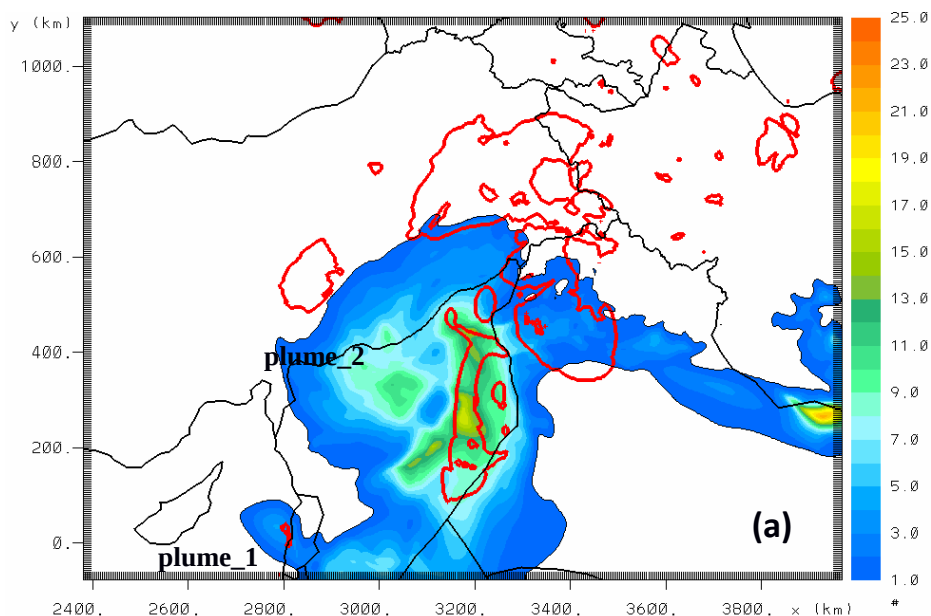
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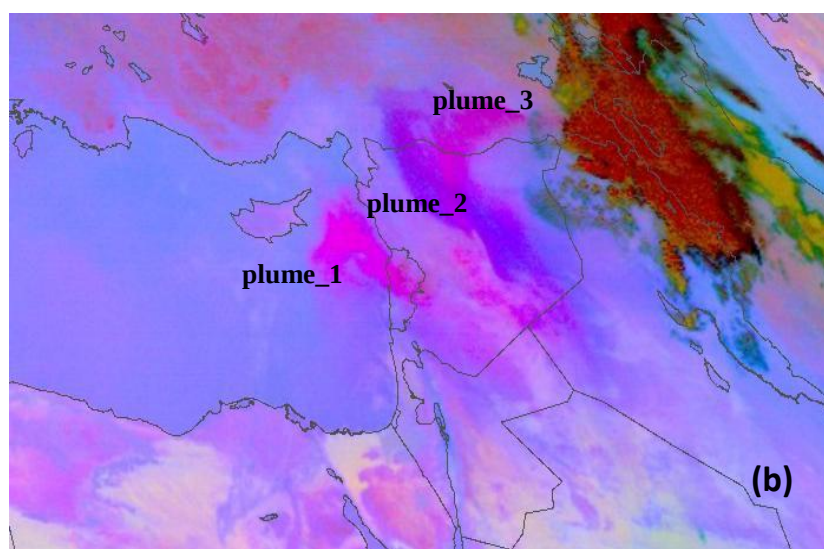
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593   Figure 5. a) Model AOD at 550 nm (color scale) and cloud cover > 70% (red contour). b) MSG-SEVIRI
594   dust RGB component, 7 September 2015, 00:00 UTC
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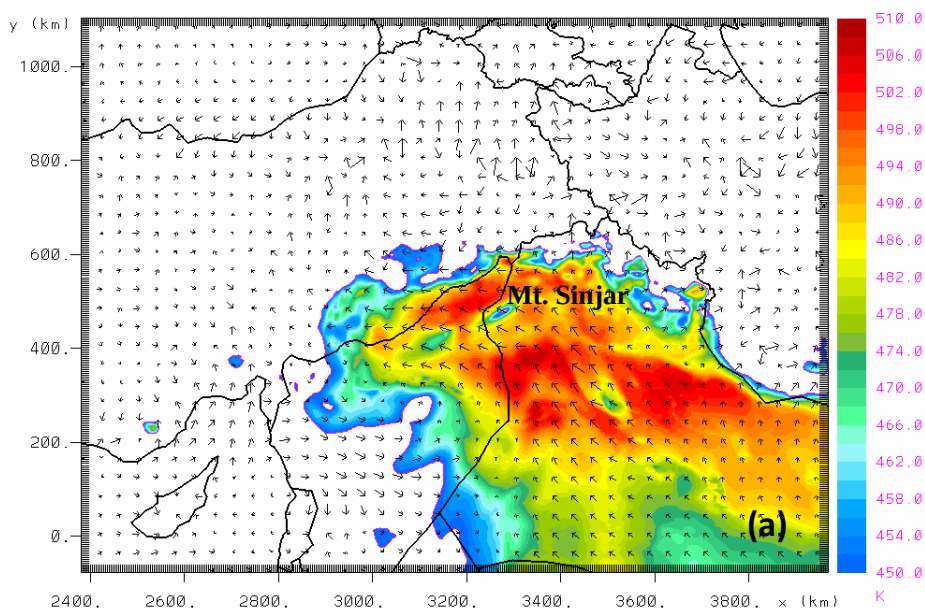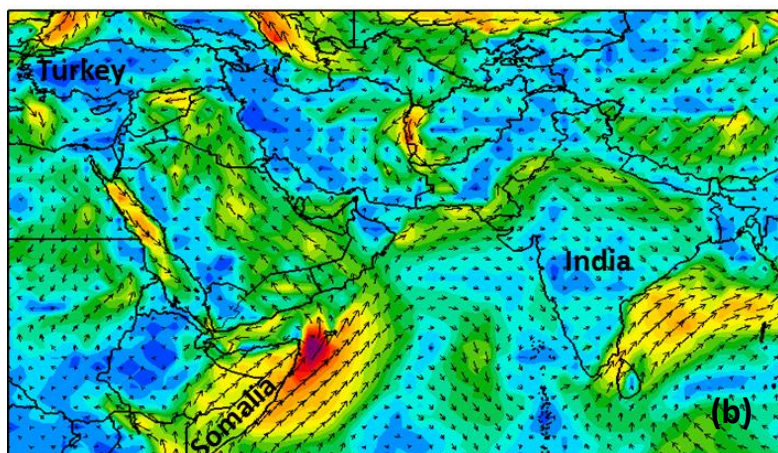
604 Figure 6. a) Model equivalent potential temperature (K) and wind vectors at 50m above ground, 6

605 September 2015, 13:00 UTC. b) Wind speed at 10m from the NCEP final analysis (FNL) dataset, 6

606 September 2015, 06:00 UTC.

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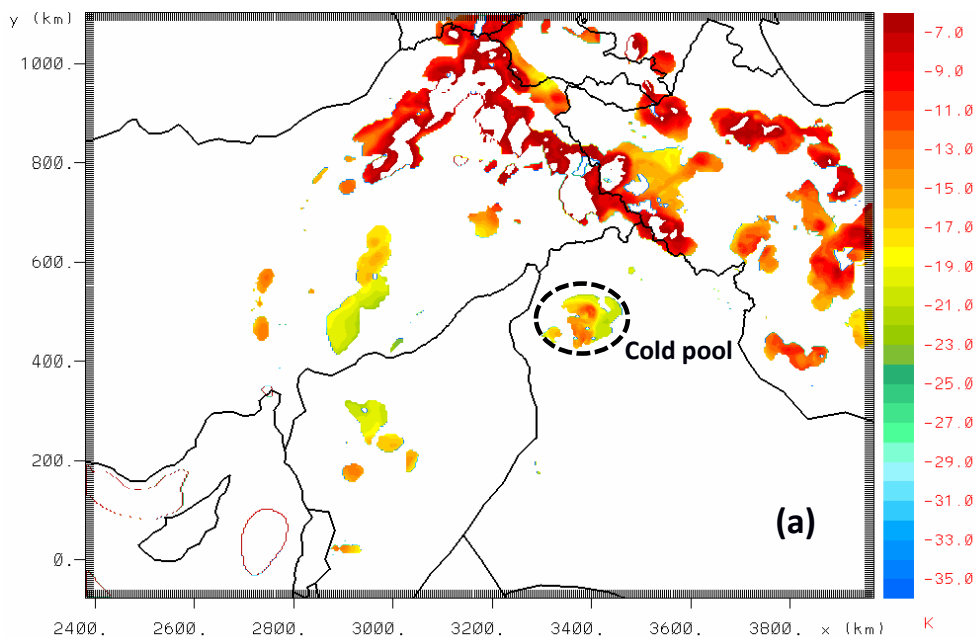
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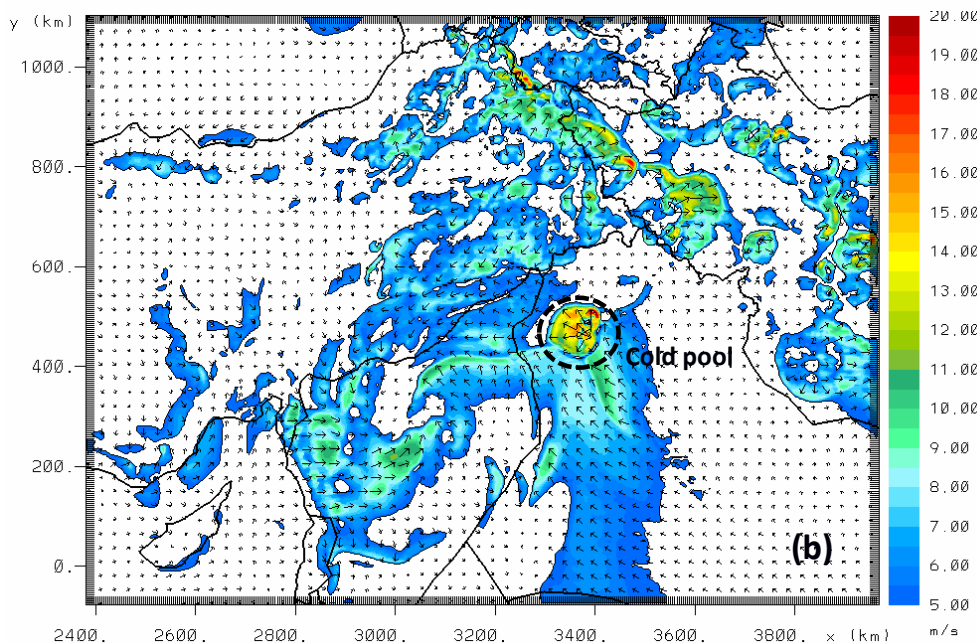
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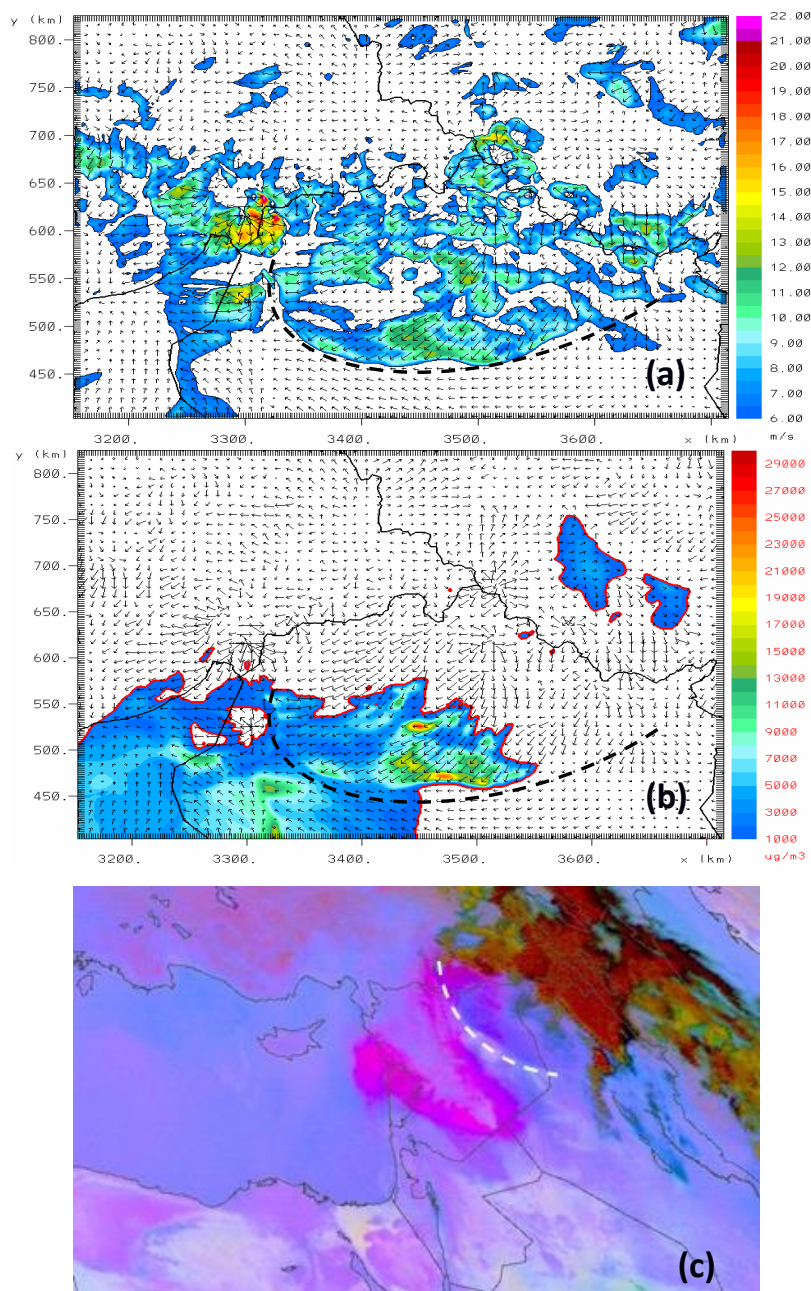
611   Figure 7. a) Model rain droplets – air temperature difference in K. b) Model wind speed at 10m (ms⁻

612   ¹), 6 September 2015, 15:00 UTC. The dashed line denotes the location of the cold pool.

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616   Figure 8. a) Model wind speed greater that 6 ms^{-1} at 10m and b) Near surface model dust

617   concentration (μg m^{-3}) from the inner grid (2×2km) c) MSG-SEVIRI RGB component, 6 September

618   2015, 20:00 UTC. The dashed lines indicates the haboob front location.

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624 Figure 9. a) MSG-SEVIRI RGB map and CALIPSO overflight (green line), b) CALIPSO dust mass

625 concentration (µg m^{-3}) and c) model dust mass concentration at 6 September 2015, 23:33 UTC. Due

626 to the severity of the event CALIPSO signal is totally attenuated bellow ~1km a.s.e. in the area

627 between 35-37°N (dark blue color).

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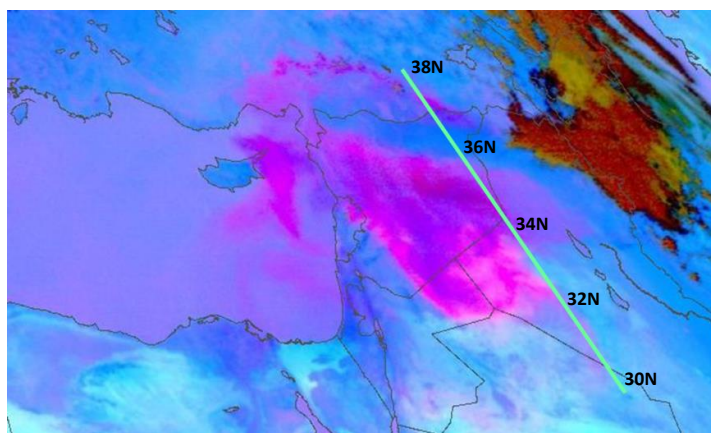
Figure 10. a) MSG-SEVIRI RGB map and CALIPSO overflight (green line), b) CALIPSO dust mass

concentration (μg m^{-3}) and c) model dust mass concentration at 7 September 2015, 10:35 UTC. Due

to the severity of the event CALIPSO signal is totally attenuated bellow ~1km a.s.e. in the area

between 34-36°N (dark blue color).

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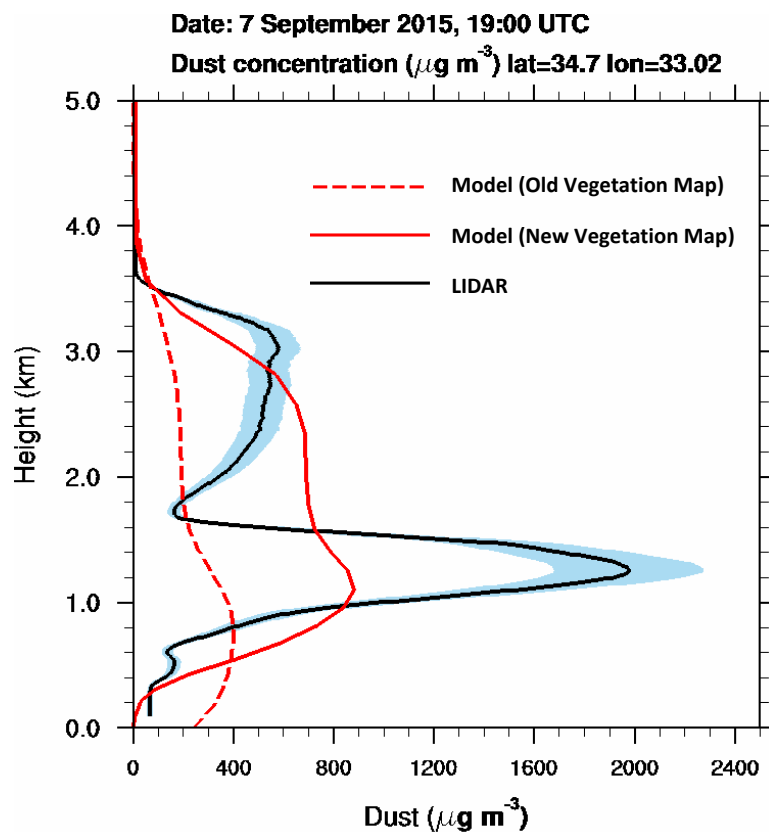
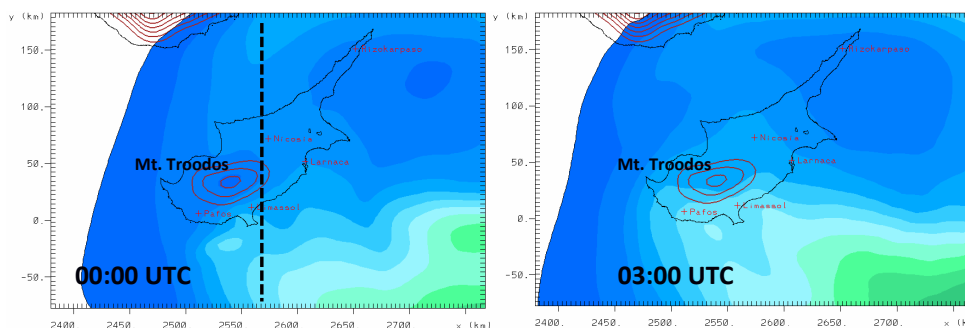
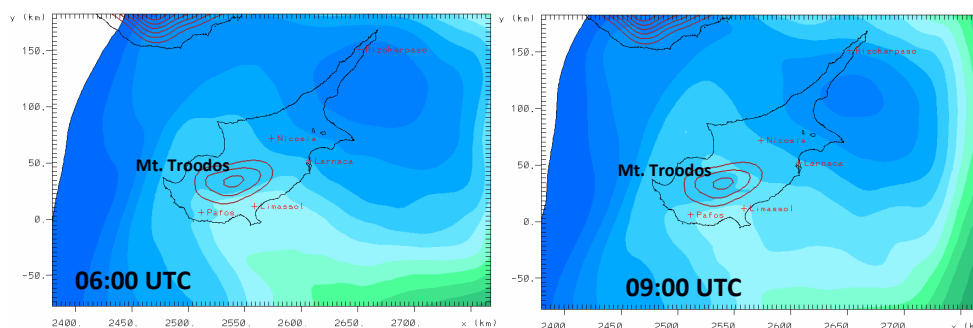
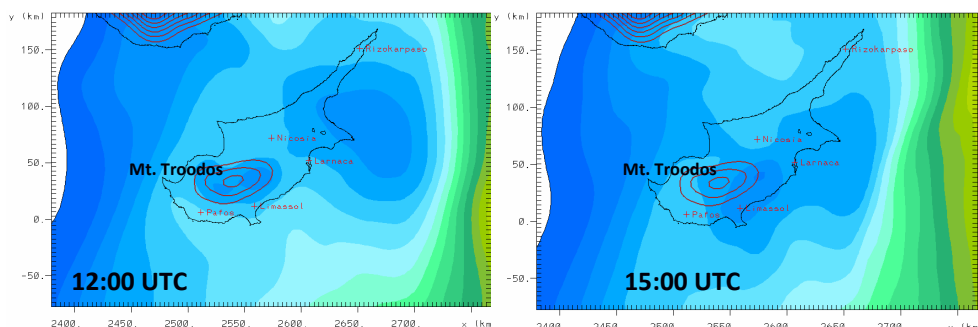

640
641 Figure 11. Vertical profile of dust concentration on 7 September 19:00 UTC over Limassol. Blue
642 shadow indicates a 20% uncertainty of the lidar measurements.

643

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647 Figure12. Model 550 nm AOT over Cyprus 00:00 – 15:00 UTC, 8 September 2015, zoom from the

648 second (4×4 km) model domain. The dashed black line shows the location of the cross-sections in

649 Figure 13.

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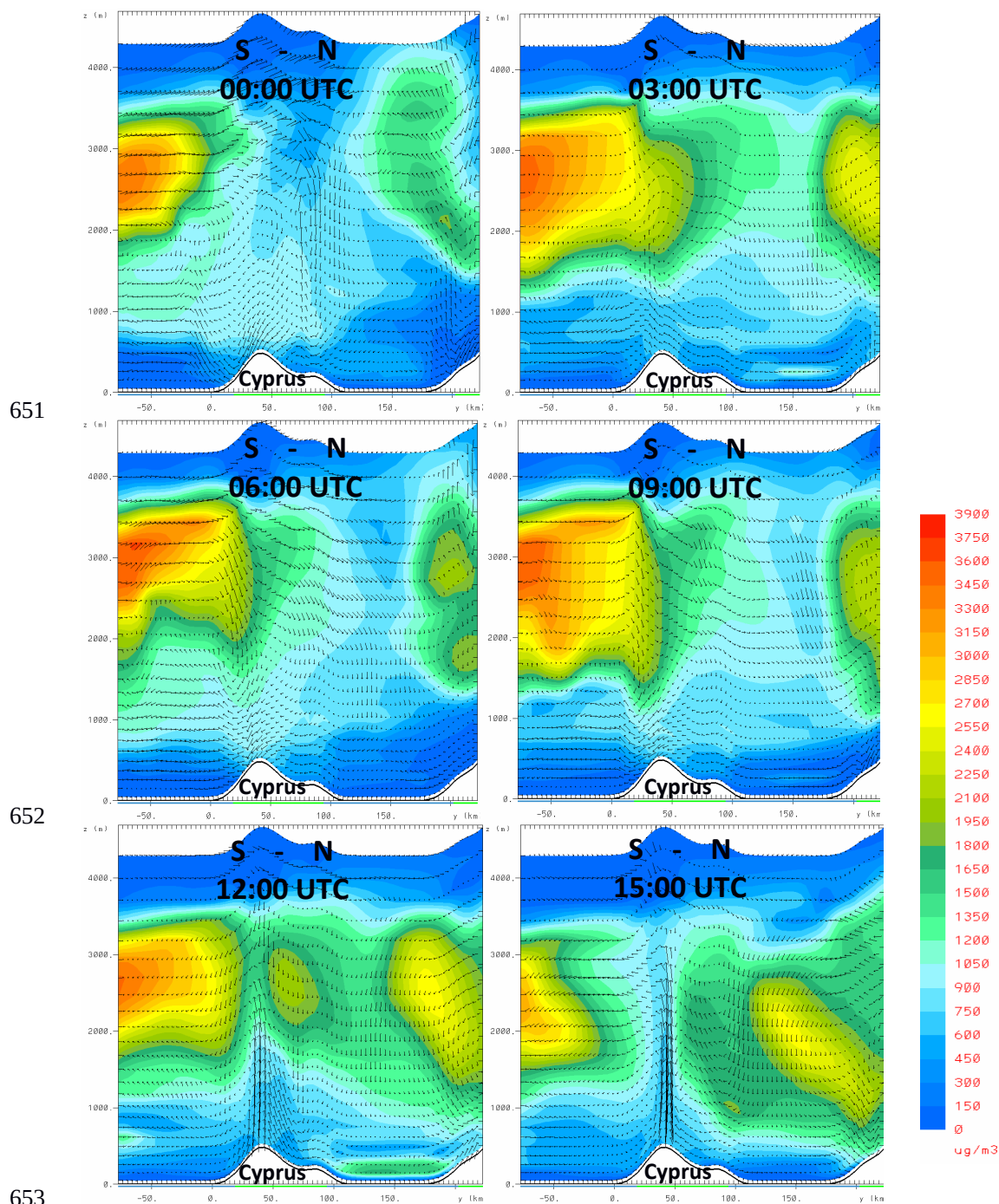
654 Figure 13. Vertical cross-section (South-North) of modeled dust concentration over Cyprus 00:00 –

655 15:00 UTC, 8 September 2015. The location of the cross-section is shown in Figure 12a.

656