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► To cite this version:

Foteini Baladima, Jennie L. Thomas, Didier Voisin, Marie Dumont, Clementine Junquas, et al.. Modeling an extreme dust deposition event to the French alpine seasonal snowpack in April 2018: Meteorological context and predictions of dust deposition. *Journal of Geophysical Research: Atmospheres*, 2022, 127 (8), pp.e2021JD035745. 10.1029/2021JD035745 . insu-03617771

HAL Id: insu-03617771

<https://insu.hal.science/insu-03617771>

Submitted on 3 Jun 2022

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1 **Modeling an extreme dust deposition event to the**
2 **French alpine seasonal snowpack in April 2018:**
3 **Meteorological context and predictions of dust**
4 **deposition**

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15 **Key Points:**

- 16 • An extreme dust deposition event occurred in April 2018, that is in the top 95%
17 of dust events to the Alps during the snow season.
18 • Wet (~80%) and dry dust deposition (~20%) contribute to total; dry deposition
19 increases up to ~1700m (~40%) in the western part of the French Alps.
20 • Differences in dust deposition when increasing the model resolution are co-located
21 with regions with improved predictions of precipitation.

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Abstract

Mineral dust is an important aerosol in the atmosphere and is known to reduce snow albedo upon deposition. Model predictions of dust deposition events in snow covered mountain regions are challenging due to the complexity of aerosol-cloud interactions and the specifics of mountain meteorological systems. We use a case study of dust deposition between 30 March and 5 April 2018 to the French alpine snowpack to study the processes that control dust deposition to the seasonal snowpack. To understand processes controlling dust transport and deposition to snow we use a combination of *in situ* observations at Col du Lautaret in the French Alps, satellite remote sensing, the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis global atmospheric composition, and the regional model WRF-Chem. Specifically, we investigate the role of increased model spatial resolution within WRF-chem in capturing mountain meteorology, precipitation, and predicted dust deposition. Regional model results are also compared to the reanalysis global CAMS products including aerosols in the atmosphere and predicted dust deposition fluxes. We conclude that predicted mountain meteorology (e.g. precipitation) is better with increased model resolution (3 x 3 km resolution WRF-Chem domain). This improved meteorology has significant impacts on predicted dry and wet dust deposition to the alpine snowpack. Dry deposition is important in the western part of the French Alps at low altitudes, while wet deposition dominates over the complex higher altitude mountain terrain.

1 Introduction

Mineral dust deposition to snow, including seasonal mountain snowpacks, can accelerate snow melting by causing a reduction in snow albedo (Painter et al., 2007, 2012, 2013; Reynolds et al., 2014; Tuzet et al., 2017; Skiles et al., 2018; Di Mauro et al., 2019). This reduction in snow albedo, referred to as snow darkening, triggers the well known snow albedo feedback mechanism in which reduced snow albedo accelerates the growth of snow grains, which further increases radiation that is absorbed and promotes snow/ice melt (Warren & Wiscombe, 1980; M. G. Flanner et al., 2007; M. Flanner et al., 2012; Hansen & Nazarenko, 2004; Tuzet et al., 2020). While dust impacts on the snow life cycle are clearly evident, accurate predictions of dust deposition in snow within mountain regions remains a challenge (Deems et al., 2013; Hock et al., 2019; Rahimi et al., 2020). This is due to a number of complex processes that contribute to accurate predictions of dust deposition starting with dust emissions, followed by transport/processing in the atmosphere within weather systems, and eventual deposition to snow within the complex mountain meteorological situation (Goudie & Middleton, 2001; Kok et al., 2012; Mahowald et al., 2014). At present, the accuracy of dust deposition rates predicted by models can limit our ability to correctly assess the impacts of dust on snowpack evolution (Tuzet et al., 2017, 2020).

Dust deposition to the mountains has recently been at the forefront of research on high altitude snowpacks (Lau & Kim, 2018; Sarangi et al., 2020; Das et al., 2020; Kok et al., 2021; Usha et al., 2021). There are two main types of deposition that result in dust arriving on/in snow: wet and dry deposition. Wet deposition is very efficient for removing aerosols from the atmosphere and occurs when aerosols are first taken up into clouds or scavenged during precipitation and then deposited with falling rain/snow (Pruppacher & Klett, 1997). Therefore, uncertainties in wet removal within mountains can be correlated with the uncertainties in predicted precipitation within models (Huneus et al., 2011; Stocker, 2014; Regayre et al., 2018). Accurate prediction of precipitation is a known challenge in mountain regions, where there are clearly interactions between mountain topography and the occurrence of orographic precipitation. Dry deposition is the other important process by which dust arrives on snow, which involves a combination of direct contact between dust plumes that are transported long distances in the low/mid troposphere, and can directly arrive at high altitude mountain snowpacks as well as gravitational settling of large particles farther aloft (Seinfeld & Pandis, 2016). Understand-

ing the interactions between dust transport and deposition within mesoscale weather systems and microscale mountain meteorological systems remains a challenge.

Before being deposited to snow, dust plays an important role in the atmosphere and has both direct and indirect radiative impacts (Hansen et al., 1997; Haywood & Boucher, 2000). Long range dust transport is inherently tied to mesoscale weather systems bringing air from Africa mainly westward and southward towards/across Atlantic by the Saharan Air Layer but also to Europe (Chiapello et al., 1997; Sodemann et al., 2006; Salvador et al., 2014; Prospero et al., 2021). Aerosols themselves also impact weather systems due to their role as cloud condensation nuclei (CCN) and ice nuclei (IN) and their indirect (secondary) impacts on clouds (formation, droplet size, cloud darkening). Aerosols are linked to precipitation via their role in modification of clouds. Dust can have a significant impact on the energy balance within the atmosphere via warming upon absorbing solar radiation, or via cooling by participating in light scattering and modification of clouds (Hansen et al., 1997; Haywood & Boucher, 2000). Models that include a full description of aerosol-cloud interactions are best adapted to fully understand the role of dust within the atmosphere.

Between 30 March and 5 April 2018 a strong dust deposition event was observed within the seasonal snowpack at Col du Lautaret in the French Alps. Snowpit measurements after 4 April 2018 show that this dust layer stayed on the top of the snowpack during the entire snowmelt period, with implications for snow albedo and snow melt for the rest of the snow season. Tuzet et al. (2020) showed using the Crocus snowpack model (Vionnet et al., 2012; Tuzet et al., 2017) that the combined impacts of all light absorbing impurities shortened the seasonal snow cover by 11 days at Col du Lautaret in 2018 (Tuzet et al., 2020). These observations provide the motivation for understanding the specific conditions that result in this dust deposition event and an evaluation of how models can best represent events of dust deposition to snow.

The present study aims to answer the following scientific questions, with a specific focus on this extreme dust event that occurred in late March/early April 2018:

1. What are the large scale atmospheric drivers for this event of dust deposition to snow?
2. Does high resolution modeling including aerosol-cloud interactions improve the representation of dust deposition to snow?
3. Is accurate representation of specific mountain meteorology important for predicting dust deposition?
4. Are both dry and wet deposition important scavenging mechanisms during this event?

In order to answer these questions, we use a combination of satellite remote sensing, *in situ* measurements, and modeling tools, including dedicated Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) model (Grell et al., 2005; J. D. Fast et al., 2006) predictions of the complete dust lifecycle. First, we present the observations and model data as well as we describe a specific WRF-Chem configuration model run conducted as part of this study in Section 2. We then present our results and discussion in Section 3. We show dust concentrations measured in snow pits during the 2018 winter-spring season in the French Alps (Tuzet et al., 2019) (Sect. 3.1). We compare 2018 to the multi-year dust transport frequency detected by satellite in Sect. 3.2. For this specific extreme dust deposition event that occurred in early April 2018, the main meteorological context is presented (Sect. 3.3). We present an evaluation of the simulated dust transport by comparing with satellite data and the Copernicus Atmosphere Monitoring Service (CAM5) reanalysis in Sect. 3.4. In Sect. 3.5, an evaluation of the WRF-Chem model predicted meteorology is performed. Finally, In Sect. 3.6 the WRF-Chem

124 model predicted dust deposition is presented and compared with CAMS reanalysis (Inness
125 et al., 2019) and observations. The summary and conclusions are presented in Sect. 4.

126 **2 Data and Methods**

127 **2.1 Measurements at Col du Lautaret**

128 Col du Lautaret is a high mountain pass located in the French Alps at 2058 m above
129 sea level (ASL) latitude=45° 02' 29" N longitude=6° 24' 38" E. The location is shown
130 in Figure 1a (magenta circle). A field campaign took place during the snow season 2017-
131 2018 with the objective of quantifying the concentrations of light absorbing impurities
132 (LAPs) in snow including dust, elemental carbon (EC) and refractory black carbon (rBC)
133 along with physical and optical properties of snow that were measured weekly. A detailed
134 description of them and their impacts on snow evolution are found in (Tuzet et al., 2019).

135 Meteorological measurements were collected for the winter season 2017-2018 us-
136 ing an Automated Weather Station (AWS). Temperature, shortwave and longwave in-
137 cident radiation, wind speed, atmospheric pressure, and relative humidity were the recorded
138 parameters (Tuzet et al., 2019).

139 **2.2 Satellite observations of aerosols, clouds, and snow**

140 **2.2.1 MODIS**

141 The Moderate Resolution Imaging Spectroradiometer (MODIS) is a passive sen-
142 sor that is onboard both NASA Aqua and Terra satellites. We use two MODIS data prod-
143 ucts in this study: aerosol optical depth (AOD) and snow cover. MODIS provides AOD
144 data based on two retrieval algorithms. The Dark-Target (DT) algorithm, which retrieves
145 data over dark surfaces and includes ocean surfaces and over vegetated/dark-soiled land.
146 The Deep Blue algorithm retrieves data over bright surfaces such as deserts. For our study
147 we use a daily product that combines these algorithms, the Dark Target and Deep Blue
148 Combined data product (Platnick et al., 2015) Collection 6.1 data (MYD08_D3). This
149 product provides daily coverage over all cloud-free and snow-free surfaces. From this we
150 use maps of AOD at 550 nm at 0.1 Degree (~10 km) spatial resolution. We also use the
151 MODIS fractional snow cover from the the daily L3 Global 500 m SIN Grid, Version 6
152 data (Riggs et al., 2015). This product is generated by using MODIS calibrated radi-
153 ance data products, the geolocation products, and the cloud mask products. MODIS AOD
154 data was downloaded from NASA Giovanni (<https://giovanni.gsfc.nasa.gov/giovanni/>)
155 and snow cover data from National Snow & Ice Data Center (<https://nsidc.org/data/MOD10A1/versions/6>).

157 **2.2.2 CALIOP**

158 Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard Cloud-Aerosol
159 Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) provides high-resolution
160 vertical profiles of aerosols and clouds through the daytime and night-time at two wave-
161 lengths, 532 nm and 1064 nm. Here we use version 4 (V4) level 2 (L2) vertical feature
162 mask (VFM) data product. The VFM algorithm takes into account the estimated par-
163 ticle depolarization ratio, the total attenuated backscatter, as well as the aerosol geo-
164 graphic location, the underlying surface type and the observed aerosol altitude (Omar
165 et al., 2009) and identifies and classifies cloud and aerosol layers. Further, upon being
166 detected aerosols are classified by type into the following categories: dust, polluted con-
167 tinental, polluted dust, smoke, clean continental, and clean marine. CALIOP data was
168 downloaded from <https://www-calipso.larc.nasa.gov/products/>.

169 **2.3 Ground based PM10 measurements**

170 We use PM10 (coarse particles with an aerodynamical diameter of 10 μm or less)
 171 measurements from surface sites in France, including mountain sites to evaluate model
 172 predictions of dust transport. Specifically we use measurements from the Atmo Auvergne-
 173 Rhône-Alpes air quality monitoring network. As part of this network PM10 concentra-
 174 tions were monitored using automated analyzers, in accordance with recommendations
 175 of EN 16450:2017. PM10 measurements for 15 sites in France (see Figure 1a, green dots)
 176 were downloaded from <https://www.atmo-auvergnerhonealpes.fr/>.

177 **2.4 Reanalysis data**

178 Reanalysis datasets are temporally, spatially, and physically consistent products
 179 that combine data from earth observing systems, including satellites and *in situ* mea-
 180 surements, with numerical model simulations (ECMWF, 2021).

181 **2.4.1 ERA5**

182 ERA5 reanalysis which is the most updated global meteorological reanalysis from
 183 ECMWF and the Copernicus Climate Change Service (C3S) (Hersbach et al., 2020). This
 184 new reanalysis replaces the ERA-Interim reanalysis and is based on the Integrated Fore-
 185 casting System (IFS) Cy41r2. ERA5 benefits from developments that have been done
 186 in model physics, core dynamics and data assimilation in the last 10 years. It provides
 187 hourly data at 0.25° by 0.25° (which is approximately ~ 27.6 km x ~ 14.6 km near the
 188 French Alps) spatial horizontal resolutions and 137 levels spanning the surface of the Earth
 189 to 0.01 hPa.

190 **2.4.2 CAMS**

191 The CAMS reanalysis (Inness et al., 2019) is the latest global reanalysis data set
 192 of atmospheric composition produced by ECMWF, consisting of 3-dimensional time-consistent
 193 fields of aerosols, trace and greenhouse gases. CAMS uses the updated IFS and the as-
 194 sociated aerosol module (IFS-AER) includes five types of aerosols including desert dust
 195 which is represented with three bins (0.03–0.55 μm , 0.55–0.9 μm , 0.9–20 μm). The dif-
 196 ferent aerosol types are externally mixed and both dry and wet deposition processes are
 197 included. The dust emissions are computed dynamically following Ginoux et al. (2001)
 198 dust source formulation and by taking into account prognostic meteorological variables,
 199 vegetation cover, soil moisture, snow cover provided by the model and the MODIS-derived
 200 UV-visible component of the land surface albedo (Morcrette et al., 2009).

201 CAMS reanalysis assimilates AOD observation from MODIS Aqua/Terra Collec-
 202 tion 6 (Benedetti et al., 2009; Levy et al., 2018) retrievals. The CAMS aerosol config-
 203 uration including AOD assimilation is described in Benedetti et al. (2019), which is based
 204 on Benedetti and Fisher (2007) and Benedetti et al. (2009). It should be noted that the
 205 vertical profile of the aerosol mixing ratio is not modified by the assimilation (Benedetti
 206 et al., 2019). CAMS reanalysis data have a global horizontal resolution of $0.75^\circ \times 0.75^\circ$
 207 (~ 80 km) and 60 vertical levels. It covers a time period from 2003 to 2020 with a tem-
 208 poral resolution of 3-hours. CAMS provide AOD datasets of multiple wavelengths, AOD
 209 data at 550 nm are used in this study.

210 **2.4.3 SAFRAN**

211 Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige (SAFRAN)
 212 is a mesoscale atmospheric analysis system from Météo-France which provides reanal-
 213 ysis data of surface meteorological variables (Durand et al., 2009). The data are provided
 214 on a grid based on mountain regions with similar meteorological characteristics called

215 *massifs* where the variability of data is a function of elevation, aspect and slope. For each
 216 massif, SAFRAN provides each parameter every 300 m at elevations up to 3600 m. SAFRAN
 217 uses an optimal interpolation to assimilate available observations including temperature,
 218 humidity and wind speed. Daily measurements including accumulated precipitation and
 219 temperature of around 500 meteorological stations over the French Alps at altitudes be-
 220 tween 200 and 2500 m are included.

221 **2.5 Precipitation data products**

222 **2.5.1 GPM**

223 Global Precipitation Measurement (GPM) is an international satellite mission ini-
 224 tiated by the Japan Aerospace Exploration Agency (JAXA) and the United States Na-
 225 tional Aeronautics and Space Administration (NASA) (Huffman et al., 2019). It pro-
 226 vides high quality next generation precipitation observations using an international con-
 227 constellation of satellites including research and operational microwave sensors at a tempo-
 228 ral resolution of 3 hours and global coverage. The Integrated Multi-satellite Retrievals
 229 for GPM (IMERG) algorithms intercalibrate, merge, and interpolate all GPM constel-
 230 lation satellites microwave precipitation estimates, together with microwave - calibrated
 231 infrared (IR) satellite estimates, precipitation gauge analyses, and potentially other pre-
 232 cipitation estimators. The latest released GPM data version 6 V06B at 0.1 Degree (which
 233 is approximately ~ 11 km x ~ 5.8 km near the French Alps) spatial resolution was used
 234 in this study. GPM data was downloaded from <https://gpm.nasa.gov/data/directory>.

235 **2.5.2 Radar**

236 Météo France provides a weather radar rainfall mosaic dataset with a spatial reso-
 237 lution of 1 km and a temporal resolution of 5 min which covers the whole metropoli-
 238 tan France. It is a network of 30 radars and the volume scan of each radar is processed
 239 every 5 min to provide a quantitative precipitation estimate (QPE) map. The estimated
 240 precipitation is obtained by composing the QPE maps creating a national radar prod-
 241 uct called PANTHERE (Projet Aramis Nouvelles Technologies en Hydrométéorologie
 242 Extension et REnouvellement). While most of the operational radars in this framework
 243 are C and S band, X-band Doppler polarimetric radars are operated over the southern
 244 Alps (Yu et al., 2018).

245 **2.6 WRF-Chem model**

246 The WRF-Chem (Grell et al., 2005; J. D. Fast et al., 2006) model is a fully online
 247 coupled model. It permits the simulations of emissions, transport, mixing and chemi-
 248 cal transformation of trace gases and aerosols simultaneously with the meteorology. The
 249 model is based on the Advanced Research WRF (ARW) core, which handles the mete-
 250 orology, physics and transport processes (Skamarock & Klemp, 2008). The aerosol and
 251 chemistry components are completely consistent with the modeled meteorology, using
 252 the same grid and transport systems and same physics schemes for subgrid-scale trans-
 253 port (Grell et al., 2005). In our study, aerosol feedbacks/effects are included through the
 254 interaction of cloud physics with the model predicted aerosols (Easter et al., 2004; J. D. Fast
 255 et al., 2006). Here we use the regional model WRF-Chem 4.1.0 including an explicit de-
 256 scription of aerosol-cloud interactions in order to quantify the relationship between dust
 257 deposition and weather systems. We set up the model using 3 nests (Figure 2), which
 258 are run using one way nesting. The model (D01) was run to include dust emissions through
 259 to deposition, from 14 March 2018 to 4 April 2018. We exclude the first 10 days of model
 260 run for D01 from analysis and consider this period as the model spinup. D01 includes
 261 the region of dust emissions in the Sahara, D02 is a regional domain over Europe, and
 262 D03 is a high resolution domain to capture the features of mountain meteorology. The
 263 meteorological initial and boundary conditions are provided by ERA5 (0.25° horizon-

264 tal resolution and 6 h temporal intervals). Chemical initial and boundary conditions (bound-
265 ary conditions only for D01) are provided from the CAM-Chem model (see [https://](https://www2.acom.ucar.edu/wrf-chem/wrf-chem-tools-community)
266 www2.acom.ucar.edu/wrf-chem/wrf-chem-tools-community, (Buchholz et al., 2019)).
267 WRF-Chem-D01 domain includes the Saharan dust emission region and no initial and
268 boundary conditions are provided for dust. For D01, spectral nudging (Miguez-Macho
269 et al., 2004) also using ERA5 is applied and updated every 6 hours above the planetary
270 boundary layer (PBL) for winds and temperature. For computational efficiency while
271 also preserving the dust transport pathway from D01 to D02 and D03, D02 and D03 are
272 run for a shorter time period. For D02 the model was run from 28 March 2018 and for
273 D03 it was run from 29 March 2018 (18:00 UTC) to 4 April 2018. For numerical stabil-
274 ity, time off-centering for vertical sound waves (*epssm*) and or the vertically propagat-
275 ing acoustic modes (*damp*) options were applied to all domains. The specific model phys-
276 ical, chemical, and emissions options for each domain are summarized in Table 1.

277 The model was run using the 8 bin Model for Simulating Aerosol Interactions and
278 Chemistry (MOSAIC) aerosol scheme (Zaveri et al., 2008) including aerosol-cloud inter-
279 actions (Easter et al., 2004; J. Fast et al., 2014), including the updates described in (Marelle
280 et al., 2017). We use this particular setup due to the advanced description of aerosol physics
281 and interactions with clouds. Specifically, MOSAIC treats aerosol processes including
282 nucleation, coagulation, condensation, and evaporation. Aerosol-cloud interactions are
283 described by aerosols acting as cloud nuclei, via in cloud chemistry, and via within and
284 below cloud wet scavenging. Interstitial (suspended in air or between cloud particles)
285 and cloud-borne aerosol particles (suspended in cloud droplets) are treated explicitly.
286 Modeled aerosols can be activated or re-suspended (in air) depending on saturation, par-
287 ticle size, and aerosol composition. MOSAIC uses a sectional approach to simulate the
288 aerosol size distributions (0.039-0.078 μm , 0.078-0.156 μm , 0.156-0.312 μm , 0.312-0.625
289 μm , 0.625-1.25 μm , 1.25-2.5 μm , 2.5-5.0 μm , 5.0-10.0 μm) of five inorganic ions (sulfate,
290 ammonium, nitrate and sea salt in the form of chlorine and sodium) and three primary
291 aerosol species (black carbon, dust, and organic matter). Modeled Black Carbon (BC)
292 includes all emitted black carbon mass that is included in the aerosol mass within MO-
293 SAIC. All particles within the same size bin are assumed to be internally mixed so that
294 all particles within a bin have the same chemical composition and interactions with liq-
295 uid clouds within each model grid cell. Within MOSAIC the hygroscopicity and CCN
296 activity nucleating ability of aerosols is a linear combination of their aerosol chemical
297 composition and considers aerosols as internally mixed within each size bin. Examples
298 of the mass fraction for each chemical component modeled within each size bins over the
299 dust emissions region and over the Alps are shown in Figure S1. Aerosol dry deposition
300 includes Brownian and turbulent diffusion as well as gravitational settling (Wesely, 1989).
301 In-cloud and below-cloud precipitation scavenging is included within the prediction of
302 wet deposition as described by Easter et al. (2004).

303 Dust emissions are calculated online using the Goddard Chemistry Aerosol Radi-
304 ation and Transport (GOCART) emissions scheme (Ginoux et al., 2001) and have been
305 modified here according to Shao et al. (2011) to be optimized for Saharan dust. The ba-
306 sic parameters of any dust emission model are the threshold friction velocity as well as
307 the horizontal and vertical mass flux of dust as wind speed near the surface should be
308 sufficient to lift surface particles and entrain them into the atmospheric boundary layer
309 (Kok et al., 2012). GOCART scheme uses the simulated from WRF-Chem wind speed
310 near the surface and calculates online dust emissions. We also modified the model to save
311 dust deposition rates for each aerosol size bin within MOSAIC.

3 Results and discussion

3.1 Observed dust deposition to snow in winter/spring 2018

Dust deposition to snow at Col du Lautaret in the French Alps (Figure 1a, magenta circle) was measured within snow pits during the 2018 snow season (Figure 1b), measurements described in Tuzet et al. (2019). Specifically, a large dust deposition event was measured in the snow pit conducted on 4 April 2018 (Figure 1b, dark red layer) that was buried slightly below the surface. Given the earlier snow pit that was completed on 13 March 2018 did not contain this layer with enhanced dust concentrations, we can clearly identify this dust deposition occurred between 13 March and 4 April 2018 (as already noted in Tuzet et al. (2019)), the time period is shown by a gray box in Figure 1b. We show the regional extent of snow cover during the same time period on 22 March 2018 in Figure 1a to depict the regional extent of alpine snow cover during the deposition event. The simulated snow cover extent during the deposition event from WRF-Chem D02 is shown in Figure S2a).

3.2 Multi-year analysis of dust transport during the alpine snow season

In this section we aim to understand how this observed dust deposition event fits into the multi-year context of dust transport during the winter season. For this, we use satellite observations of AOD from MODIS Aqua and reanalysis values of AOD from CAMS using all data available from 2002 to 2021. The availability of MODIS AOD retrievals over snow covered areas is significantly limited by high albedo as well as by the frequent occurrence of cloud cover (see Supplement, Figure S2b). To overcome this limitation, we use a larger region than the snow covered Alps (2.5°E , 38.5°N , 11.5°E , 48.5°N , region shown in inset of Figure 3) to identify dust transport events. We calculate the average AOD within this region as a daily average shown in Figure 2. The highest average AOD values that lie above the 95th percentile (teal points) and above the 99th percentile (magenta points) thresholds for AOD values for the snow season (noted in gray, December to April) are shown. We classify consecutive days with enhanced AOD as the same dust transport event. The red cross shows our specific dust transport event that occurred in early April 2018. This analysis allows us to characterize this as extreme event due to the fact that it is among the top 5 percentile of all dust transport events during snow season between 2002-2021. Looking at AOD MODIS retrievals from 13 March to 4 April (data not shown), we identified that this dust transport event occurred between 31 March 2018 and 3 April 2018. We show the AOD MODIS retrievals for the key period in Sect. 3.4.

3.3 Mesoscale meteorological conditions in this dust deposition event

AOD from MODIS and CAMS shown in the prior section provided the specific time window when this dust transport event occurred, between 31 March 2018 and 3 April 2018. In this section we show the prevailing atmospheric circulation patterns that dominate during this dust transport event that results in deposition to snow. The days before and during the dust outbreak are impacted by the negative North Atlantic Oscillation (NAO) phase (Meteo France, 2021). When NAO is negative, both sub-polar low and subtropical high are weaker than average, the Atlantic Jet Stream has a more zonal (west-to-east) orientation which results in a convergence of winter Atlantic storms in central west Europe.

The synoptic conditions of the dust event are described using the ERA5 reanalysis. In Figure 4a we show the 700 hPa geopotential height at 12:00 UTC from ERA5 on each of the days of the event. On 1 April 2018 (Day-2) a ridge extended over north central Africa while a trough extended from east Europe to the Mediterranean sea (Fig-

361 ure 4a). On 2 (Day-1) and 3 (Day 0) of April the ridge axis moves eastwards causing south-
 362 westerly flow, over the Mediterranean sea towards the French Alps, with high wind speeds
 363 (up to 10 m/s at sea level in Figure S3a and 20 m/s at 700 hPa height Figure 4a). At
 364 the surface, a high-pressure system centered between Sicily and center-north Africa ex-
 365 tends up to Algeria while a thermal low pressure system extends over north Africa in-
 366 cluding Morocco (see supplement Figure S3a Day-1 and Day-2). Additionally, a low pres-
 367 sure system (Atlantic low) is displaced towards northwest of Spain. Large amount of wa-
 368 ter vapor is transported in the Alps (see supplemental Figure S3b) and precipitation events
 369 are expected in the region. All of these factors result in a dust enriched air mass that
 370 is transported from the Sahara and arrives at Col du Lautaret with this weather system
 371 on 3 April 2018.

372 We compare WRF-Chem D01 with ERA5 geopotential height at 700 hPa to eval-
 373 uate the model ability to reproduce the meteorology that drives this event (Figure 4).
 374 WRF-Chem D01 captures well the general circulation during all the days of the event.
 375 The model is able to represent the timing and the horizontal extent of both ridges and
 376 troughs. The strength of the simulated Saharan high is slightly overestimated compared
 377 to ERA5 reanalysis data (on average ~ 50 m) during the event. Major differences between
 378 ERA5 and WRF-Chem D01 occur on 31 March (Day-3) when the model shows stronger
 379 wind speed and higher geopotential height at 700 hPa.

380 3.4 Evaluation of modeled dust transport

381 The AOD simulated by WRF-Chem (D01) over the dust source region and dur-
 382 ing long range transport are compared to MODIS Aqua AOD and CAMS AOD in Fig-
 383 ure 5. On the 30 and 31 March the dust plume extends over Algeria and Tunisia and
 384 on 31 March dust is clearly transported into the region of southern Italy and Sicily in-
 385 cluding the central Mediterranean Sea. The spatial distribution of the predicted AOD
 386 from both WRF-Chem and CAMS are in a good agreement with the satellite measure-
 387 ments. On 2 and 3 April the dust plume shifted west and moved to the southern part
 388 of France and southeast Spain. The lack of satellite AOD retrievals over France and the
 389 Alps is due to cloud coverage and/or the presence of high albedo snow, limiting a direct
 390 comparison between MODIS and the models as the dust plume arrives further north on
 391 2-4 April.

392 Comparing the models with the observed AOD values, we note that CAMS agrees
 393 well with AOD, while WRF-Chem tends to over-predict AOD in the dust emissions source
 394 regions (by ~ 0.15). We note that AOD is assimilated into the CAMS reanalysis (Benedetti
 395 et al., 2009; Levy et al., 2018) and a very good agreement is therefore expected. There
 396 is no assimilation of AOD or aerosol in WRF-Chem. As a result, no correction is applied
 397 to the over-prediction of the intensity of the plume, which is clearly over Africa, where
 398 WRF-Chem predicts high AOD values over a larger spatial extent than detected by MODIS.
 399 We have specifically used the parameters for the Saharan dust within the GOCART dust
 400 emissions scheme within WRF-Chem according to Shao et al. (2011). Upon adjusting
 401 these parameters, the total dust emission are reduced and lower AOD is predicted com-
 402 pared to the standard version of the model (see supplemental Figure S4). However, a
 403 general over prediction of winds by WRF-Chem at the surface in Africa compared to ERA5
 404 (see supplement, Figure S5) is the likely cause of the enhanced AOD values compared
 405 to MODIS. The simulated dust concentrations vary due to the differences in the treat-
 406 ment of aerosols and differences in simulated meteorology. In addition, CAMS includes
 407 assimilation of satellite derived aerosol AOD, while WRF-Chem does not include any
 408 assimilation. Both CAMS and WRF-Chem use similar dust emission schemes. The dust
 409 emission fluxes, which result in these atmospheric concentrations also differ due to dif-
 410 ferences in simulated surface meteorology (atmospheric stability and surface wind speed),
 411 surface properties (such as soil particle size distribution, surface roughness and soil mois-
 412 ture) as well as the models resolutions. For example, the spatial resolution of soil mois-

413 ture and vegetation cover can affect the estimated values of AOD and the dust storm
 414 spatial distribution.

415 To understand if this general over estimation of dust emissions impacts our WRF-
 416 Chem model prediction, we have completed FLEXPART-WRF potential emissions sensi-
 417 tivity (back trajectory) analysis (see supplement, Figure S6). This shows that the main
 418 dust emission source region for air that arrives at Col du Lautaret on 3 and 4 April 2018
 419 was in the very northern portion of Africa, where WRF-Chem predicted dust is in bet-
 420 ter agreement with the MODIS AOD values than the largest portion of this dust storm
 421 farther south.

422 The vertical distribution of dust in the atmosphere is important for the residence
 423 time of the dust particles and their atmospheric transport pathways. The atmospheric
 424 lifetime and transport distance for dust particles increases when it is lifted and trans-
 425 ported higher in the atmosphere. On Figure 6 we compare aerosols within the atmosphere
 426 detected by CALIOP (aerosol detection and aerosol sub-type) for the CALIPSO over-
 427 passes shown in black on Figure 6. We show the four overpasses that capture this dust
 428 transport event: one on 31 March, one on 3 April, and two on 4 April. For this, we ex-
 429 tract the total concentration of dust from the CAMS results (all dust bins) and WRF-
 430 Chem model (other inorganic aerosols, which are primarily dust using D01) along the
 431 CALIPSO overpass and provide a vertical profile along each overpass. We show that the
 432 aerosol retrievals from CALIOP are limited by the location of high altitude clouds above
 433 8 km for some overpasses. These include: 10-15 deg Lat (Figure 6a), 35-45 deg Lat (Fig-
 434 ure 6c), and 40-50 deg Lat (Figure 6d). Clouds limit the ability to directly detect the
 435 main portion of the dust transport event during deposition to snow over the Alps, on
 436 4 April. However, we can still evaluate the representation of dust farther south and prior
 437 to being transported into the region. The aerosol layer detected by CALIOP (orange color,
 438 Figure 6 panels (a-d) for all CALIPSO overpasses is mainly identified as dust (yellow color,
 439 Figure 6 panels (e-h)) by the VFM mask algorithm.

440 First, we look how the models represent dust near the source region on 31 March
 441 and 2 April 2018. On 31 March (Figure 6, first column) the dust layer extends up to 6 km
 442 altitude and as far north as 33°N in the satellite retrievals and in both models outputs.
 443 Satellite measurements between 10°N and 17°N are missing due to cloud attenuation.
 444 On 2 April (Figure 6, second column) the dust layer was lifted higher in the mid tropo-
 445 sphere up to 7 km according to CALIOP. The WRF-Chem model captures the depth
 446 of the dust layer for this overpass, but the simulated dust plume peak is shifted further
 447 north compared to the measured satellite retrievals. However, the CAMS dust layer be-
 448 tween 5°N and 20°N is lifted higher in the atmosphere than detected by CALIOP.

449 We now look at dust as it arrived over Europe and the region of the Alps, we look
 450 at the overpasses on 4 April 2018, which is during the deposition event. Both CALIPSO
 451 overpasses on this day (Figure 6 (g) & (h)) show there are thick clouds in the mid-troposphere
 452 at latitudes spanning from 40°N to 50°N. For these latitudes the signal is attenuated and
 453 we cannot compare the horizontal and vertical distribution of the dust plume over the
 454 Alps. Both models show that a significant dust plume is transported to the region of the
 455 Alps on 4 April. However, the vertical distribution of the modeled plumes for both over-
 456 passes are represented differently in WRF-Chem and CAMS. In general, WRF-Chem has
 457 a smaller vertical extent of the plume with a more concentrated dust layer near the sur-
 458 face, which is in agreement with CALIOP. CAMS predicts a dust layer that extends higher
 459 into the atmosphere, which is in less good agreement with the CALIOP retrievals. The
 460 vertical extent of the dust plume plays a key role for the dust particles lifetime and trans-
 461 port. The lifetime of dust particles within the PBL is relatively short due to turbulent
 462 mixing. Dust particles in the free troposphere have a longer transport distance due to
 463 their longer lifetime and they can later be entrained into the local mixed layer i.e through
 464 the cloud-top by cloud-induced mixing. While the exact connection between the verti-
 465 cal extent of the plume and deposition rates over the Alps is not well quantified, we note

466 that ensuring accurate vertical distribution and co-location with clouds is important for
 467 wet removal, while accurate dust concentrations near the ground are clearly important
 468 for accurate prediction of dry deposition.

469 In Figure 7, we compare WRF-Chem (blue line) and CAMS (green line) aerosol
 470 predictions to 15 ground based air quality monitoring station (black line) to evaluate if
 471 the model captures correctly dust that is transported to the region of the French Alps
 472 during this event. We show a comparison between WRF-Chem (D01) and CAMS (3-hourly
 473 data) predicted PM10 and the Atmo Auvergne-Rhône-Alpes air quality observations, which
 474 include three types of measurement sites (urban, semi-urban, and background), in Fig-
 475 ure 7. For this we use modeled predicted surface value (lowest model level) and inter-
 476 polate the results to the latitude and longitude of each measurement site. We use all three
 477 types of measurements sites that are part of this air quality network for our evaluation.
 478 The exact timing of the arrival of this dust storm in the French Alps is noted in the gray
 479 background on all panels.

480 Both models in general capture the scale of PM10 before and during the event. CAMS
 481 predicts PM10 values though shows a bias more pronounced than WRF-Chem D01 val-
 482 ues when compared to observations over the whole time period. This bias is often caused
 483 by an increased night-time bias and can be correlated with the strong diurnal cycle which
 484 is more pronounced in CAMS. The PBL height and evolution impacts the PM10 mea-
 485 surements but the key mechanisms may vary at the different altitudes and sites. Sur-
 486 face dust concentrations from both models and observations causes surface PM10 to in-
 487 crease significantly during the event in all measurements sites across the French Alps.
 488 This increase shows that air pollution in the region can be caused by non local sources.
 489 However, we note that the urban and semi-urban sites (such as Chamonix and Demi-
 490 Quartier) do not agree as well with the WRF-Chem outside the times of this specific dust
 491 event. Moreover we note that both models overestimate surface PM10 during the event
 492 at some measurement sites (such as Ordonnaz, Bourg en Bresse, Saint-Germain-Sur-
 493 Rhone). This reveals that the predicted dust plume from both models has higher dust
 494 concentrations compared to the observations closer to the surface.

495 We show that both timing and quantity of dust transport to these sites, which are
 496 located at a variety of altitudes (from 125 to 1243 m ASL) is correctly represented by
 497 WRF-Chem. This evidence provides us confidence that within WRF-Chem dust within
 498 the atmosphere can be used for accurate predictions of dust deposition to snow in the
 499 region of the the Alps.

500 **3.5 Evaluation of WRF-Chem predicted mountain meteorology and pre-** 501 **cipitation**

502 *3.5.1 Predicted regional scale precipitation and temperature*

503 In this section, we evaluate regional scale predicted WRF-Chem meteorology us-
 504 ing GPM satellite precipitation data, ground based Météo France Radar rainfall prod-
 505 uct, SAFRAN reanalysis data and ground station measurements. First, we look at the
 506 influence of model resolution on predicted precipitation in order to understand how dif-
 507 ferences in precipitation rates may be impacted model predictions of wet deposition of
 508 dust.

509 The spatial distribution of daily precipitation rates simulated by WRF-Chem, and
 510 observed by GPM and the Météo France Radar product is illustrated on Figure 8. The
 511 rain rates are qualitatively well reproduced by the model as well as the spatial variabil-
 512 ity of the daily values. WRF-Chem D02 predicts higher precipitation rates than D01,
 513 which are mainly driven by the differences in the spatial resolution of the topography.

514 On 4 April (see Figure 8, last row) during the deposition event, WRF-Chem D03
 515 underestimates precipitation over the Alps compared to both GPM and Radar products,
 516 while using a convection permitting configuration (cumulus scheme deactivated) at this
 517 resolution ($3\text{ km} \times 3\text{ km}$ horizontal resolution). These values are also lower than WRF-
 518 Chem D01 and D02 resolution predictions, where this precipitation event is produced
 519 by convective precipitation. We note that WRF-Chem D03 should be able to explicitly
 520 reproduce convection processes and associated precipitation through the description of
 521 the cloud micro-physical processes (see Table 1). Therefore, in our base run there is no
 522 convective parameterization activated in D03. To check if including parameterized con-
 523 vection in D03 improves the predictions of precipitation on 4 April we have completed
 524 a sensitivity run with a convective parameterization activated for this day (results in Fig-
 525 ure S7). When activated, the model uses both the cumulus scheme and microphysics to
 526 produce precipitation. This increases the daily simulated precipitation over the western
 527 mountain sides while decreases the simulated precipitation in the center and north east
 528 part of the Alps. Figure S7 illustrates the convective and non convective daily precip-
 529 itation during this day as well the differences of total precipitation between the two runs.
 530 The relatively high amount of convective precipitation implies that mainly the scale of
 531 convective patterns on the western side of the Alps is smaller than 3 km and the model
 532 is not able to explicitly reproduce them through microphysical processes.

533 The total predicted mean daily precipitation during the event at D01, D02 and D03
 534 resolutions as well as their differences are presented on Figure 9b and 9d. Figure 9a shows
 535 the topography over the French Alps at the 3 different resolutions. The main differences
 536 between them (Figure 9c) are depicted at the summits and ridges up to 1200 m as well
 537 as valleys. Differences in topography can alter surface moisture and consequently can
 538 influence precipitation patterns. Topographic features may stay unresolved while smoothed
 539 topography can enhance vapor transport to high elevations, increase available moisture
 540 and reduce stability. Increasing the resolution, the distribution of precipitation follows
 541 the higher topographical representation of the Alps (Figure 9b), revealing the importance
 542 of the accurate topography representation when simulating orographic precipitation. The
 543 relationship between the elevation differences and precipitation during the event when
 544 increasing the resolution shows an increase in precipitation related to the representation
 545 of orography (see supplement, Figure S8). Specifically, the differences maps (Figure 9d)
 546 show higher precipitation rates over mountain peaks and dryer valleys when increasing
 547 the resolution.

548 SAFRAN data provides wide spatial coverage (French Alps) with high accuracy
 549 at different altitudes (Durand et al., 2009). The accurate representation of the spatial
 550 distribution of precipitation is crucial for a reliable estimation of wet deposition at dif-
 551 ferent elevations over the French Alps. In order to overcome the spatial inconsistencies
 552 caused by the different grid representation of WRF-Chem outputs and SAFRAN reanal-
 553 ysis product, WRF-Chem data have been adjusted to SAFRAN semi-distributed grids/massifs.
 554 Figure 10 shows the spatial distribution of the co-located SAFRAN and WRF-Chem D01,
 555 D02, D03 mean temperature (at 2 m) Figure 10a) and precipitation (Figure 10b) dur-
 556 ing the 30 March and 3 April event at different altitudes.

557 A systematic cold bias is shown in the simulated mean 2 m air temperature by all
 558 model resolutions D01, D02, D03 and at all altitudes (Figure 10a). This bias has a high
 559 dependence on model resolution. By increasing the resolution the cold bias is moderated
 560 up to 2100 m altitude. We note that even massifs with significant mis-represented al-
 561 titudes by the WRF-Chem topography have large temperature cold biases. This is a quite
 562 well known WRF problem and several studies have underlined it (Kumar et al., 2012;
 563 Jiménez & Dudhia, 2013; García-Díez et al., 2013; Karki et al., 2017; Meng et al., 2018).
 564 The spatial distribution and magnitude of precipitation is in general well captured by
 565 the model at the different altitudes (Figure 10b). Specifically, at low altitudes (below
 566 1200 m) the simulated values from WRF-Chem are in a good agreement with SAFRAN

reanalysis data. At higher altitudes the model overestimates mean precipitation in the southern region and underestimates it in the north-west region of the French Alps compared to SAFRAN reanalysis. This bias is more pronounced for D03 and can be correlated with the pronounced cold bias in the simulated surface temperature at these altitudes. On 4 April WRF-Chem D03 resolution predicts only high altitude precipitation (above 2100 m) and underestimated mean precipitation in the lower altitudes when compared to SAFRAN (see supplement, Figure S10b).

3.5.2 Col du Lautaret

A comparison of the *in situ* observations at Col du Lautaret and the simulated values by WRF-Chem D01, D02, D03 of temperature, wind speed, specific humidity and precipitation is shown in Figure 11. It should be noted that the difference of the actual elevation of the measurement station and of the model grid cell station elevation is 191 m (D01), and 176 m (D02), 78 m (D03). A bias correction has not been applied as the aim of this work is to highlight the impact of the different model resolution to the predicted meteorology relevant to dust deposition events over complex terrain.

Figure 11a shows the time series of the hourly 2 m simulated temperature from WRF-Chem and 3.53 m from the ground observed temperature at Col du Lautaret during the simulated period. The diurnal cycle is well represented by the model. Temperature simulated from WRF-Chem D03 is in close agreement with measured values than WRF-Chem D01 and D02 between 30 March and 2 April, confirmed by RMSE values (see supplement Figure S11a). D01 and D02 are mainly underestimating the 2 m temperature by up to 6 K and 5 K respectively. D03 overestimates the 2 m temperature during the dust deposition event (light gray shaded area in Figure 11); during this period D01 and D02 are in a better agreement with the observations.

The accurate representation of precipitation is crucial for the calculation of wet removal of aerosol such as dust. The observed values have been derived from snow height measurements. The daily values are shown in Figure 11b. The precipitation events during the simulated period are in general underestimated in comparison to observations of the main snow event that contributed to dust deposition on 3-4 April. It should be noted that there is a shift on the timing of the precipitation that occurred on 1 April (12 hours) while the timing of the precipitation event between 4 and 5 April is accurately captured by the model. Precipitation events can be local phenomena and may be produced by convective rain, therefore our WRF-Chem D03 resolution of 3 km cannot fully reproduce them.

Wind speed at 10 m has an important effect on the horizontal transport of air masses. The underestimation or overestimation of wind speeds can lead to a misrepresentation of dry or/and wet deposition flux. We should underline that the wind speed measurements of the weather station at Col du Lautaret are at 5.18 m from the ground and are compared with the 10 m wind speed from the model. This can cause systematic biases between the measurements and the simulated values. Figure 11c shows an overestimation in mean wind speed more pronounced for D01 and D02 than D03 caused by the overestimation of the maximum wind speed values (see also boxplot supplement, Figure S11b). Specific humidity time-series during the simulated period are shown in Figure 11d. The model is in general in a good agreement with observed values during the simulated period.

In summary WRF-Chem model captures well the temporal evolution of the meteorological conditions during the dust event. The simulated mountain meteorology from WRF-Chem highest resolution D03 shows in general a better agreement with observations compared to WRF-Chem D01 and D02 spatial resolutions. The synoptic circulation is well represented from WRF-Chem, the horizontal resolution of 3 km is not enough though to resolve all the relevant topographic features over complex terrain. Wind speed,

618 temperature and precipitation can alter wet and dry deposition rates over the Alps via
 619 the interaction of regional atmospheric circulation and mountain boundary layer dynam-
 620 ics. A study that quantifies the advection and entrainment of free tropospheric air en-
 621 riched with dust aerosols during the boundary layer development is needed.

622 3.6 Predicted dust deposition

623 In this section we show the predicted total wet and dry deposition from WRF-Chem
 624 (at different resolutions) and CAMS and compare this with estimates derived from cor-
 625 recting model predicted dust deposited rates from the ALADIN model (as described in
 626 Tuzet et al. (2019)) that were adjusted to correctly predict the dust concentrations mea-
 627 surements in snow pits (from here on, we refer to these data as *observations*).

628 We also investigate the influence of terrain resolution topographical features both
 629 on wet and dry deposition processes. In the previous sections we discussed the represen-
 630 tation of dust within the atmosphere in both WRF-Chem and CAMS and precipitation
 631 rates over the Alps from WRF-Chem. Here, we look at how dust transport, mountain
 632 specific terrain, as well as weather/local scale meteorological processes impact predicted
 633 dust deposition rates.

634 First, we focus on understanding simulations of dust deposition locally at the Col
 635 du Lautaret site. Figure 12 compares hourly accumulated wet (Figure 12a) and dry (Fig-
 636 ure 12b) dust deposition to snow at Col du Lautaret from WRF-Chem (D01, D02, D03)
 637 and CAMS with observations. The timing and magnitude of the simulated wet and dry
 638 deposition rates by WRF-Chem are in a good agreement with the observed values. There
 639 is no significant difference between the different model resolutions specifically at the Col
 640 du Lautaret site. There is a shift in the timing of the dust deposition event that is pre-
 641 dicted by CAMS. The WRF-Chem model underestimates dust wet deposition by approx-
 642 imately a factor of 3.7 (D01), 3.9 (D02) and 2.9 (D03) compared to the observed accu-
 643 mulated value during the event. In contrast, CAMS underestimates this wet deposition
 644 value by a factor of ~ 7.7 . Dry deposition is underestimated from WRF-Chem by a fac-
 645 tor of 4.5 (D01), 9.1 (D02), 3.9 (D03), and by a factor of 20.7 from CAMS. In summary,
 646 there is no clear improvement in WRF-Chem predicted dust deposition values specifi-
 647 cally at Col du Lautaret upon increased model resolution, despite the improved regional
 648 meteorology (including precipitation) for D03 (see Section 3.5). The model predictions
 649 would require an even higher resolution than 3 km in order to represent the intersection
 650 of three different mountains at this site which are very close in proximity. However, all
 651 WRF-Chem domains are closer to the observed peak deposition values than the CAMS
 652 predictions.

653 Next, we look at the regional scale influence of WRF-Chem model resolution on
 654 dust deposition rates and compare them with CAMS and regional precipitation patterns
 655 and terrain characteristics in Figure 13. We show the total (first row) wet (second row)
 656 and dry (third row) accumulated deposition rates on 3 April 2018 at different model res-
 657 olutions. In order to overcome the spatial inconsistency caused by the different horizon-
 658 tal resolutions WRF-Chem D01 and D02 simulated values have been regridded to D03
 659 horizontal resolution.

660 The dust deposition rates simulated by WRF-Chem D01, D02, D03 show that the
 661 event includes both wet and dry deposition of dust with a larger contribution of wet de-
 662 position. Wet deposition dominates over the Alps, where we predict deposition rates over
 663 10^3 mg m^{-2} in southern part of the French Alps. The higher differences between the dif-
 664 ferent domains (D03-D01, D03-D02) are found to be co-located with the maximum dif-
 665 ferences in predicted precipitation (see supplement Figure S12). The total and wet de-
 666 position increases over the Alps and decreases over the Po valley located at the eastern
 667 part of the French Alps for the highest resolution domain (D03, 3×3 km resolution). We
 668 compare WRF-Chem lowest resolution (27×27 km resolution) model results with the CAMS

669 reanalysis product (D01-CAMS). The contribution of wet deposition to the total dust
 670 deposition rate predicted by CAMS is significant. Total and wet deposition rates from
 671 CAMS are lower by up to 3 orders of magnitude than the WRF-Chem D01 predicted
 672 values. Wet deposition is directly linked with cloud formation and precipitation and this
 673 bias is maybe caused and/or impacted by the CAMS representation of both wet removal
 674 in clouds and precipitation. To better understand this, we plot ERA5 accumulated pre-
 675 cipitation and we show that is co-located with the accumulated wet deposition on 3 April
 676 2018 (Supplement Figure S13). In summary, there are large differences in wet deposi-
 677 tion predictions which implies that different parameters are governing the wet scaveng-
 678 ing in different models and at different model resolutions (i.e vertical air mass fluxes, ver-
 679 tical distribution of precipitation, particle sizes). A study that separates the removal by
 680 convective and synoptic precipitation will give a better understanding of these differences.

681 The dry deposition rates are highest in the western part of the French Alps, where
 682 the dust plume is most present in the atmosphere (prior to rain out over the highest moun-
 683 tains in the Alps) and dust can deposit via either turbulent dry deposition (surface con-
 684 tact) or gravitational settling (dust deposition from aloft). The Saharan dust is trans-
 685 ported over the Alps by a westerly flow and as a result dry deposition is most prominent
 686 on the western side of the massifs. The strongest impact of model resolution on dry de-
 687 position is an increase in dry deposition in the western Alps (following ~ 1000 m con-
 688 tour interval) and a decrease in dry deposition for just east, where the terrain is above
 689 ~ 1000 m (Figure 13). Dry deposition at the western Alps is the same order of magni-
 690 tude as wet. Figure 14a shows the estimated (from WRF-Chem D03) altitude depen-
 691 dence of dry to total dust deposition at the western French Alps (longitude less than 6.5°E).
 692 The percentage of dry deposition increases with altitude from ~ 800 m to ~ 1700 m and
 693 decreases at higher altitudes, peaking at ~ 1700 m. Dry deposition contributes $\sim 30\%$ to
 694 $\sim 40\%$ (mean values) up to ~ 1700 m to the total dust deposition rates while it decreases
 695 up to less than 10% at higher altitudes above ~ 1700 m. The PBL height over western
 696 Alps follows a similar distribution (increases) as dry deposition rates up to ~ 1700 m (Fig-
 697 ure 14b). Depending on the horizontal wind shear with respect to the altitude, Alpine
 698 sites can be within the PBL which contains dust enriched air mass, and favors dry dust
 699 deposition. CAMS predicts lower dry deposition rates (by up to 2 orders of magnitude)
 700 compared to WRF-Chem D01. These differences originate from differences in dry de-
 701 position velocities, model topography, as well as differences in vertical distribution of dust
 702 in atmosphere.

703 In summary, models resolutions play an important role in dust transport and de-
 704 position processes over the French Alps. Mountains specifically impact precipitation via
 705 orographic lifting of air masses that leads to conversion of the condensate to precipitable
 706 particles by a combination of smaller-scale convection, turbulent air motions, and cloud
 707 microphysics (Rotunno & Houze, 2007). High-resolution simulations treat the orograph-
 708 ically forced precipitation in a more physically accurate way that is consistent with moun-
 709 tain terrain, which is essential for wet deposition. Moreover, the higher 3 km resolution
 710 domain (WRF-Chem D03) may represent more accurately the channelization of the dust
 711 flow through valleys (Bessagnet et al., 2017). The more accurate topography represen-
 712 tation can alter the mountain-valley circulation and may block the simulated dust fronts,
 713 limiting the dust transport.

714 We show that the range of the simulated deposition fluxes from WRF-Chem and
 715 CAMS varies. To better understand and address the reasons for such differences, we show
 716 the spatial distribution of dust deposition fluxes (total, wet and dry) at each size bin over
 717 the French Alps, from both WRF-Chem and CAMS (Figure 15) on 3 April 2018. WRF-
 718 Chem deposition fluxes from the first 4 size bins ($0.039\text{-}0.078 \mu\text{m}$, $0.078\text{-}0.156 \mu\text{m}$, 0.156-
 719 $0.312 \mu\text{m}$, $0.312\text{-}0.625 \mu\text{m}$) have been accumulated and presented here at one size bin (0.039-
 720 $0.625 \mu\text{m}$) (first column).

721 Over the Alps, the simulated deposition fluxes are strongly dominated by the coarse
 722 size bins i.e particles with diameters over $0.9\mu\text{m}$ for CAMS and $1.25\mu\text{m}$ for WRF-Chem.
 723 However, CAMS exhibits a general underestimation of deposition fluxes (total, wet and
 724 dry) compared to WRF-Chem over the region at these size bins. The WRF-Chem de-
 725 position size bin scheme (MOSAIC) has 3 bins over this range ($1.25\text{-}2.5\mu\text{m}$, $2.5\text{-}5.0\mu\text{m}$,
 726 $5.0\text{-}10.0\mu\text{m}$), where the gradient of deposition velocity is high, while CAMS has only
 727 one ($0.9\text{-}20\mu\text{m}$). As a result, coarse dust particles from CAMS may be affected mainly
 728 by dry and/or wet deposition processes near the dust source area. Moreover, CAMS shows
 729 a more important contribution of fine dust particles (diameters less than $1\mu\text{m}$) to wet
 730 and total dust deposition over the Alps compared to WRF-Chem. This reveals that these
 731 differences may come from first, the variations of the simulated vertical mass flux of dust
 732 (saltation flux) from the surface and/or its distribution into the dust emission bins from
 733 CAMS and WRF-Chem schemes. Second, the different simulated vertical distribution
 734 and the particle size distribution within the atmosphere from WRF-Chem and CAMS
 735 affects dust transportation and deposition. Finally, CAMS assimilates AOD MODIS re-
 736 trievals therefore modelled optical properties may shift towards observations even when
 737 the modelled microphysical properties differ. Finer particles exerts a larger effect on aerosol
 738 extinction coefficient per unit mass than coarse particles and may be fine-tuned to rep-
 739 resent the observed optical depth.

740 In Figure 15(c) we show the simulated dust deposition (total, wet and dry) at all
 741 size bins from the highest (D03) WRF-Chem resolution. Model resolution has a strong
 742 impact on spatial distribution of dust deposition at all size bins, with more pronounced
 743 differences at dust deposition fluxes related to size bins with high dust deposition rates
 744 (above $0.625\mu\text{m}$). By increasing the resolution, the spatial distribution of dust depo-
 745 sition (total, wet and dry) is altered and more dust is deposited over the Alps follow-
 746 ing the higher representation of the topography (D03). It should be noted that the main
 747 size bins that contribute to the dust deposition remain the coarse size bins and is dom-
 748 inated by dust particles located between $2.5\text{-}5.0\mu\text{m}$ and $5.0\text{-}10.0\mu\text{m}$. Dust distributions
 749 simulated from WRF-Chem are in agreement with dust measurements in snow/ice over
 750 the Alps ($3\text{-}5\mu\text{m}$ Wagenbach and Geis (1989); μm $3.2\text{-}8.5\mu\text{m}$ Di Mauro et al. (2019))

751 In summary, both models capture the timing of the dust event, although the in-
 752 tensity is underestimated. Wet deposition is seen to be the dominant removal mecha-
 753 nism during this specific event, while the dry deposition can play an important role at
 754 particular low altitudes at the lee side of the massifs. Wet deposition contributes ~ 79.5
 755 % and dry deposition $\sim 20.5\%$ to total simulated deposition rates from WRF-Chem D03
 756 (wet deposition 84.5% and dry deposition 15.5% at altitudes above 850 m). Dust coarse
 757 size bins dominate simulated deposition fluxes during this event from both CAMS and
 758 WRF-Chem model.

759 Model aerosols in the lowest and mid troposphere and aerosols scavenging processes
 760 within the models and model resolutions play an important role and drive the uncertain-
 761 ties and errors in the magnitude of wet deposition rates. A combination of factors should
 762 be taken into account when simulating and representing deposition rates over mountains
 763 i.e the French Alps. First, the magnitude and vertical extension of the dust plume that
 764 is transported into the mountain region is important both for wet and dry deposition.
 765 Second, mountain meteorology can alter aerosols scavenging by clouds. Third, the rep-
 766 resentation of aerosol cloud interactions (explicit treatment of aerosols as CCNs and INs)
 767 and scavenging processes changes in different models and model resolutions.

768 4 Summary and conclusions

769 In this paper, we focus on understanding the factors that control dust deposition
 770 to snow in the French Alps using a case study in April 2018 using satellite remote sens-

771 ing, modeling, and observations in the Alps. We first focus on understanding model pre-
772 dictions at regional scale and of mountain meteorological conditions.

773 Our study contributes to link local and regional scale processes which drive dust
774 deposition in remote mountain regions. It provides a basis of understanding the processes
775 and uncertainties on modeling dust deposition events over mountains at different res-
776 olutions. The effect of spatial resolution on model simulated mountain meteorology in-
777 cluding precipitation is specifically explored. Our results show that the WRF-Chem model
778 meteorology is very sensitive to model resolution, which is due to the improved repre-
779 sentation of topography. Increasing the resolution the updraft wind speeds and the con-
780 vective updraft areas changes and alters the simulated meteorology. A future ensemble
781 study is needed to quantify these changes as a function of dust concentration and en-
782 vironmental conditions.

783 We also use remote sensing and ground based observations of aerosols (MODIS AOD,
784 CALIOP retrievals, PM10 measurements) to evaluate both WRF-Chem and CAMS rep-
785 resentation of this dust transport event. WRF-Chem model overestimates AOD and sur-
786 face PM10 during the event while underestimates deposition fluxes compared to obser-
787 vations at Col du Lautaret. CAMS reanalysis assimilates MODIS AOD retrievals and
788 a good agreement between MODIS and CAMS AOD is shown. CAMS overestimates the
789 surface PM10 values and underestimates dust deposition fluxes compared to both ob-
790 servations and WRF-Chem D01 simulated values. The comparison of deposition rates
791 between WRF-Chem D01 and CAMS shows a difference, mainly correlated to wet de-
792 position, up to 3 orders of magnitude.

793 A combination of factors results in the underestimation of deposition fluxes at Col
794 du Lautaret despite the overestimation of aerosol mixing ratio within the atmosphere
795 compared to observations from both models. First the overestimation/underestimation
796 of dry deposition velocity can overestimate/underestimate size bins concentrations of dust
797 particles transported in the atmosphere. Moreover, biases and errors in the magnitude
798 and timing of precipitation have a significant impact on the wet deposition rates. Sec-
799 ond, the representation of aerosol-cloud interactions within the different models and res-
800 olutions can alter the number of dust aerosols that are activated and act as CCNs and
801 INs. The explicit treatment of aerosol as ice nuclei is not included in the WRF-Chem
802 version used in this study (Berg et al., 2015). Uncertainties of scavenging processes of
803 aerosols within and below clouds impacts the deposition rates.

804 A better understanding of how orographically forced precipitation events are im-
805 pacted in the presence of dust is crucial for the better understanding of wet removal pro-
806 cesses. A study that quantifies the removal by convective and synoptic precipitation over
807 mountain regions during dust events will give us a better understanding of the dominant
808 processes and their uncertainties.

809 In summary, we have shown:

- 810 • An extreme dust deposition event occurred in April 2018, that is in the top 5%
811 of dust transport events to the Alps during the snow season detected by satellite
812 between 2002-2021 snow seasons.
- 813 • Dust for this event was transported to Col du Lautaret specifically from the north-
814 ern portion of Africa, representing a filament of a larger dust transported event
815 that transported a significant amount of dust farther east.
- 816 • This dust transport event occurred within a developing storm that resulted in sig-
817 nificant precipitation (snow/rain) as it arrived in the Alps.
- 818 • Model predictions of dust deposition to snow have different spatial and tempo-
819 ral properties, with mainly under predicted wet deposition to the Col du Lautaret
820 site.

- 821 • For this event, WRF-Chem model predicts that both wet ($\sim 79.5\%$) and dry de-
822 position ($\sim 20.5\%$) contribute to total dust deposition. (wet deposition 84.5 % and
823 dry deposition 15.5% at altitudes above 850 m over the Alps)
- 824 • Dry deposition is a key removal process at the western part of the French Alps
825 at low altitudes, while wet deposition dominates over the complex higher altitude
826 mountain terrain.
- 827 • Our specific WRF-Chem setup improved dust deposition predictions compared
828 to CAMS, when evaluated against observations.
- 829 • The main differences in model predicted deposition are not co-located with the
830 measurement site, but instead are located at lower elevations for dry deposition
831 and co-located with improved predictions of precipitation (for D03) for wet de-
832 position.
- 833 • Total dust deposition for this event increase in the Alps and decreases at Po Val-
834 ley upon increasing model resolution (WRF-Chem D03).
- 835 • Deposition fluxes over the Alps are strongly dominated by the coarse size bins i.e
836 particles with diameters over $0.9\mu\text{m}$ for CAMS and $1.25\mu\text{m}$ for WRF-Chem dur-
837 ing this event.

838 This study shows that WRF-Chem predicts the full lifecycle of dust from initial
839 emissions, transport and processing in the atmosphere, and removal via wet and dry de-
840 position but improvements in model dust emissions and aerosol scavenging is needed.
841 For example, a better representation of dust emissions within WRF-Chem by improv-
842 ing soil moisture data from satellite retrievals could improve the dust particle mass dis-
843 tribution, thus impacting emissions, transport, and deposition processes. In addition,
844 measurements of dry deposition velocities over the domain of interest could help us bet-
845 ter estimate the emitted and transported dust and may help us improve the dry depo-
846 sition parameterizations within the model. Furthermore, the explicit treatment of aerosol
847 as ice nuclei could improve dust scavenging from clouds. This study also shows that CAMS
848 predicts well dust concentration within the atmosphere but underestimates dust depo-
849 sition fluxes for the simulated event at Col du Lautaret. The episodic nature of dust de-
850 position can result to inter-annual fluctuations of seasonal snow melt rate and shorten-
851 ing of snow season. The accurate representation of dust deposition fluxes is important
852 for quantifying these changes. The underestimation of dust deposition fluxes over glaciers
853 and seasonal snow cover mountain regions can have a significant impact on projections
854 of future climate change.

Table 1. WRF-Chem 4.1.0 setup.

Description	D01 (27×27 km)	D02 (9×9 km)	D03 (3×3 km)
Physics options and inputs			
Planet. bound. layer	YSU (Hong et al., 2006)	→	→
Surface layer	Revised MM5 Scheme (Jiménez et al., 2012)	→	→
Land surface	Noah-MP(Niu et al., 2011)	→	→
Microphysics	Morrison (Morrison et al., 2009)	→	→
SW radiation	Dudhia Scheme (Dudhia, 1989)	→	→
LW radiation	RRTM Longwave Scheme (Mlawer et al., 1997)	→	→
Cumulus param.	Kain-Fritsch - CuP(Berg et al., 2015)	→	See note ^a
Mountain Options	Not activated	Not activated	See note ^b
Physics initial cond.	ERA5 (Hersbach et al., 2020)	→	→
Physics bound. cond.	ERA5 (Hersbach et al., 2020)	D01	D02
Chemistry options and inputs			
Aerosol chem.	MOSAIC 8 bins (Zaveri et al., 2008) with VBS-2 SOA formation & aq. chem.	→	→
Gas-phase chemistry	SAPRC-99(Carter, 2000)	→	→
Chemical initial cond.	CAM-Chem (Buchholz et al., 2019)	→	→
Chemical bound. cond.	CAM-Chem (Buchholz et al., 2019)	D01	D02
Anthro. emiss.	CAMS (Granier et al., 2019)	→	→
Fire emiss.	FINN (Wiedinmyer et al., 2011)	→	→
Biogenic emiss.	MEGAN (Guenther et al., 2006)	→	→
Dust emiss.	GOCART (Chin et al., 2002) ^c	→	→

^aa sensitivity run with this on also for D03 was completed

^bslope effect on surface solar radiation, shadowing of neighbouring grid cells

^cupdated according to (Shao et al., 2011)

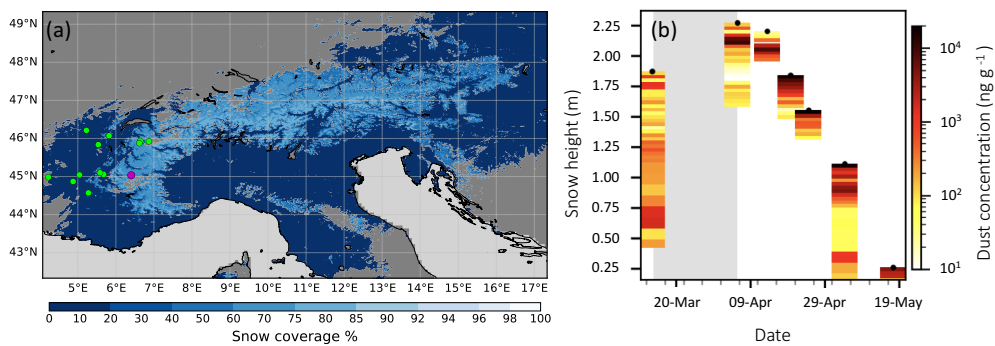


Figure 1. (a) Spatial extent of snow cover in the Alps on 22 March 2018 from MODIS/Terra. Magenta cycle presents Col du Lautaret site. Green circles show the location of ground PM10 measurement sites used in Figure 7. (b) Dust concentrations measured in snow pits at the Col du Lautaret during spring 2018 originally published in (Tuzet et al., 2019). Light gray shaded area corresponds to dust deposition events that occurred between 13 March and 4 April 2018. High dust concentration measurements are depicted with dark red color. Each black dot corresponds to a snowpit measurement. Snow height is given as height above ground level.

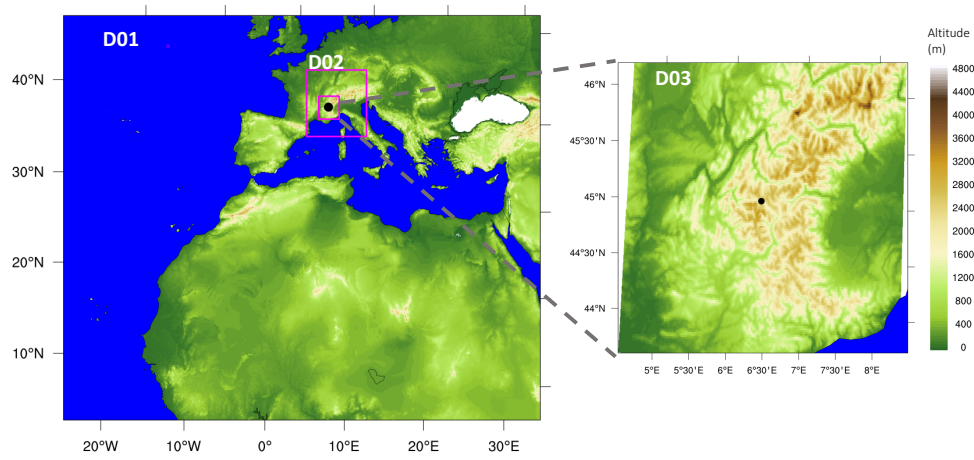


Figure 2. The WRF-Chem simulation domains (and associated horizontal model resolutions): D01 (27 km), D02 (9 km), and D03 (3 km, zoom in on right). The model topography (color bar) and domain boundaries (pink) are shown.

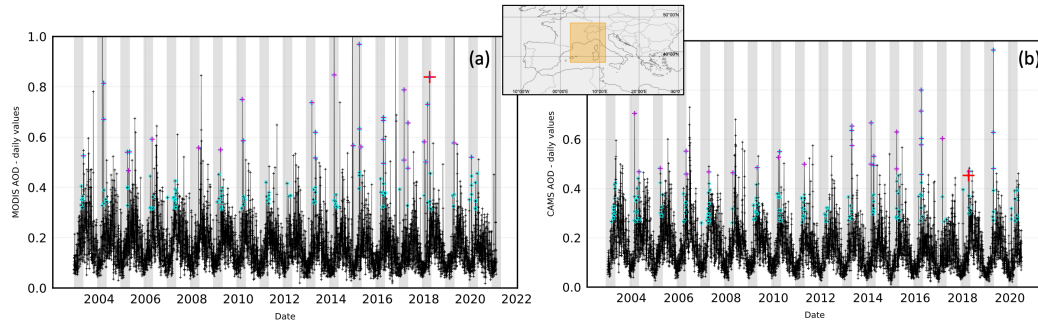


Figure 3. Time series of the spatial average over the box : 2.5°E , 38.5°N , 11.5°E , 48.5°N (inset pane) of daily mean AOD from MODIS Aqua (550 nm) (a) and CAMS reanalysis (b) for the period July 2002/2003 to February 2020/2021. Magenta and teal cycles present the 95 and 99 percentile of AOD during the snow season (December to April) accordingly. The Red Cross presents the simulated dust event in April 2018. Light gray shaded areas correspond to the snow season (December-April).

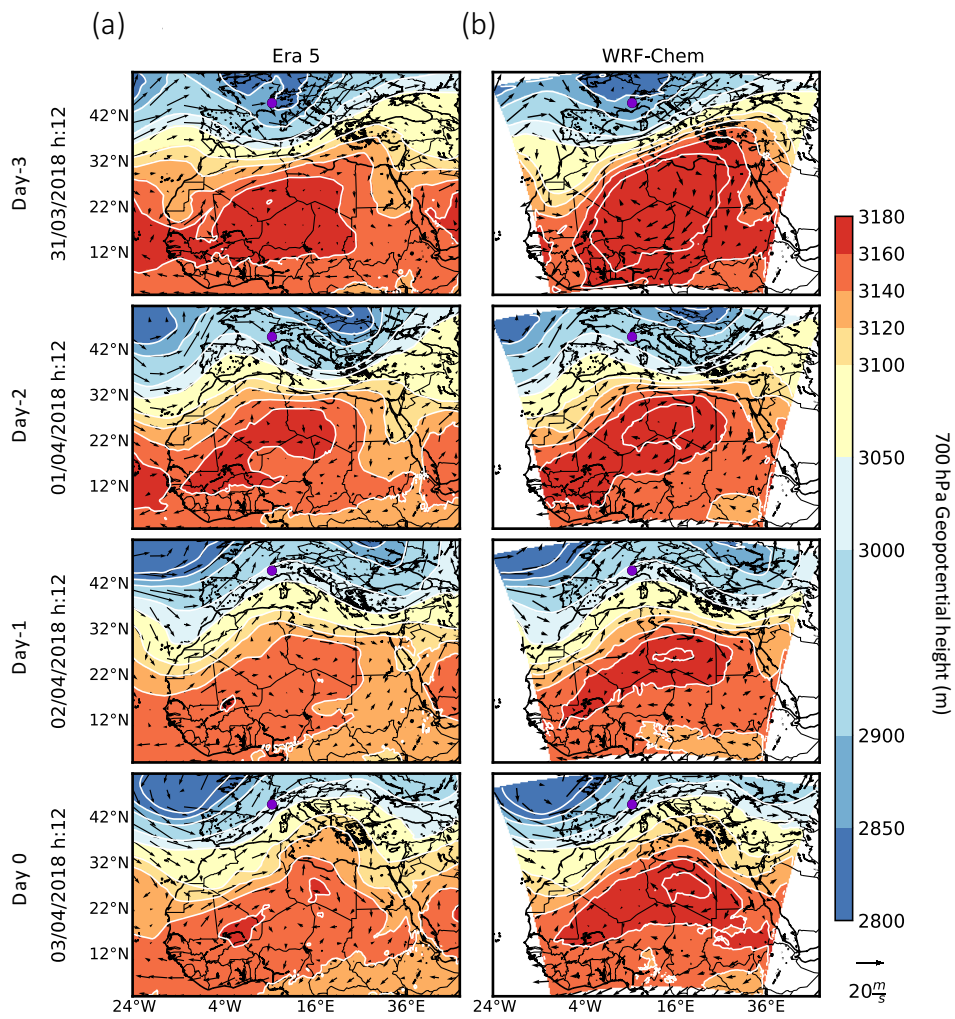


Figure 4. 700 hPa Geopotential height (contour) and wind speed (arrows) (a) from ERA5 (b) from WRF-Chem at 12:00 UTC from 31 March to 3 of April 2018.

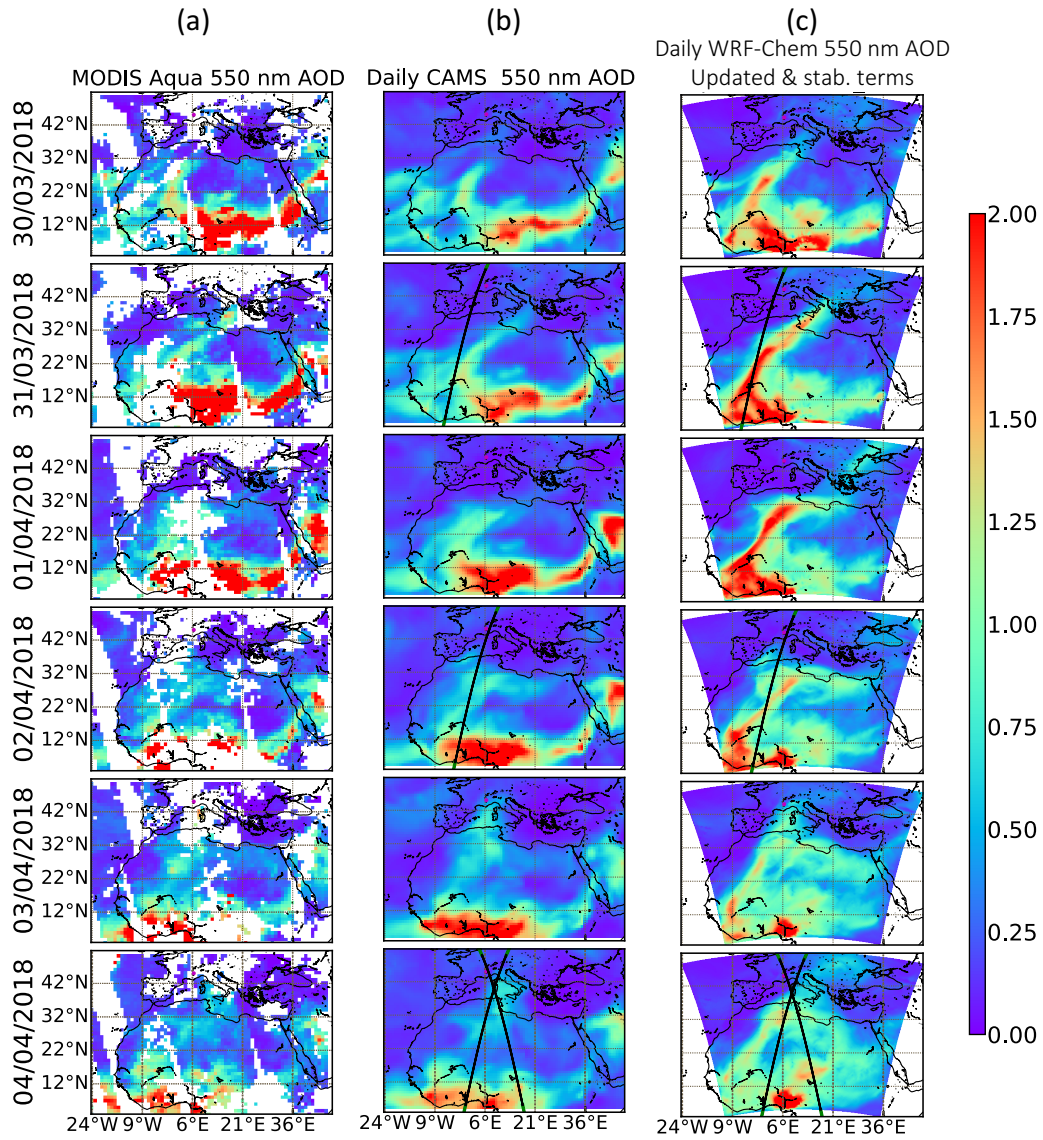


Figure 5. The 550 nm AOD from 30 March to 04 April 2018 from MODIS Aqua (a-f) compared to CAMS reanalysis (g-l) and WRF-Chem D01 simulated values (m-r) on the same days. CALIPSO overpasses are shown in black and green; the black portion of the overpass indicates the data used in Figure 5.

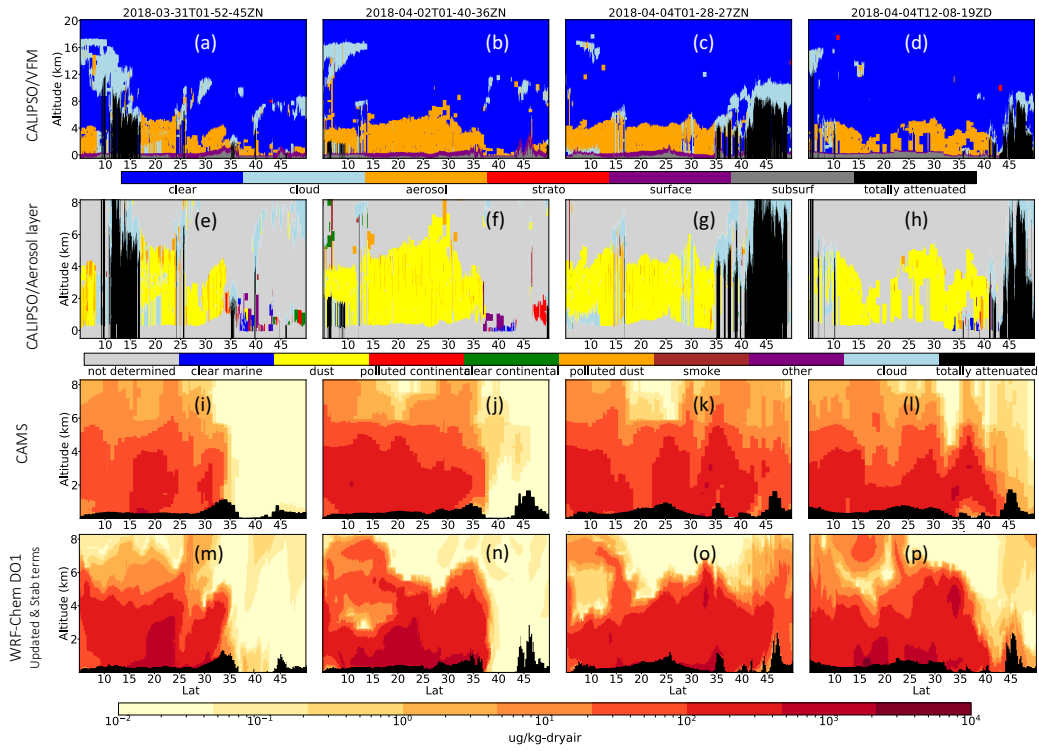


Figure 6. First row panels (a-d) show the Vertical feature mask (VFM) from the CALIPSO overpass on 31 March 2018 (01:52 UTC to 02:06 UTC), 2 April 2018 01:40 UTC to 01:54 UTC), 4 April 2018 (01:28 UTC to 01:42 UTC), 4 April 2018 (12:08 UTC to 12:21 UTC). Second row panels (e-h) show the vertical sub-types of aerosols, yellow color indicates dust. Third row panels (i - l) show the CAMS reanalysis and fourth row panels show WRF-Chem model results of dust mixing ratio extracted along the overpasses.

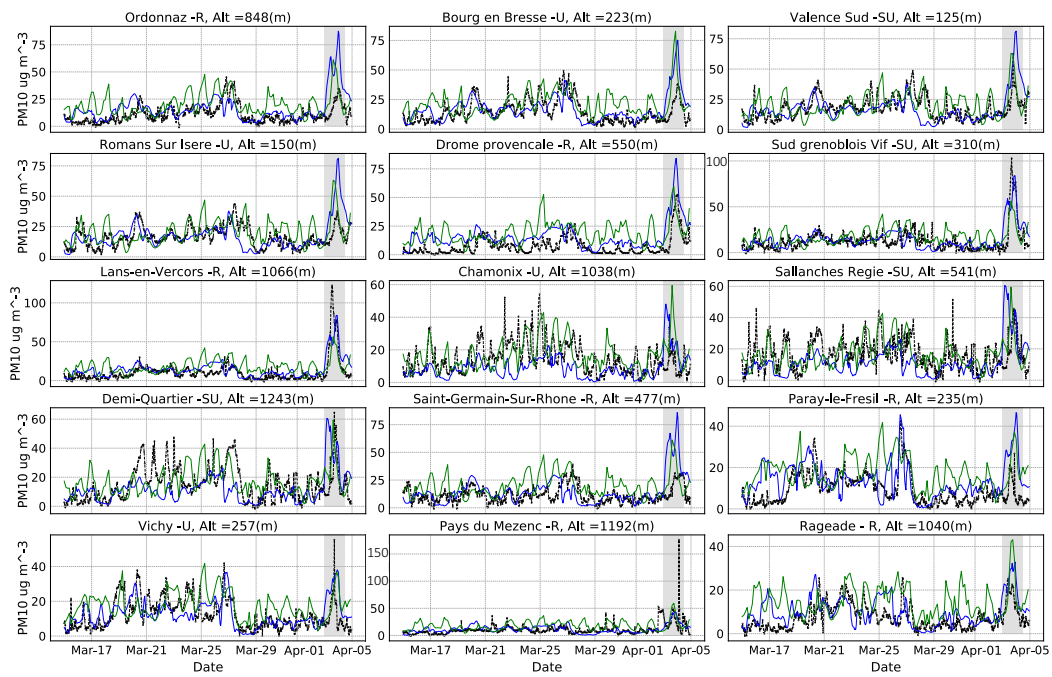


Figure 7. Hourly PM10 mass observations near the French Alps (black color) and the corresponding WRF-Chem D01 simulated values (blue color) and CAMS values (green color) for 15 March 2018 to 5 April 2018. Light gray shaded area corresponds to dust deposition event for the period 3 April and 4 April 12:00 UTC 2018.

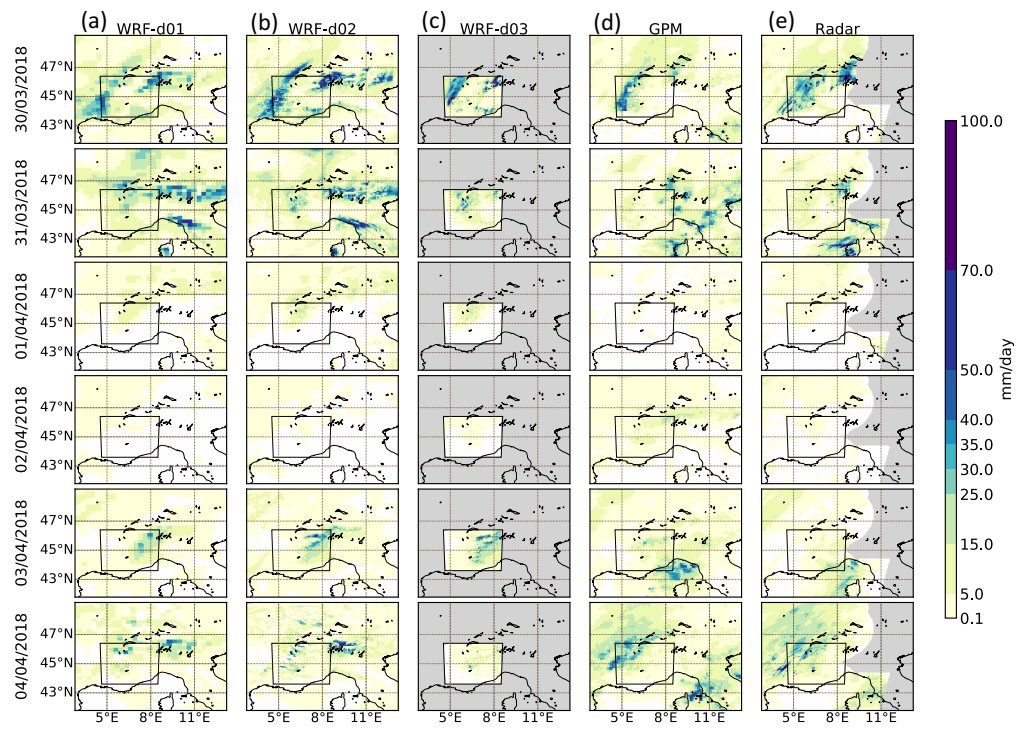


Figure 8. Spatial distribution of co-located WRF-D01 - (a), WRF-D02 - (b), WRF-D03 - (c), GPM - (d), Météo-France Mosaic Radar - (e), total daily precipitation from 30 March to 4 April. Grey color indicates no data; white color indicates daily precipitation less than 0.1 mm/day. The inner black box depicts the perimeter of WRF-D03.

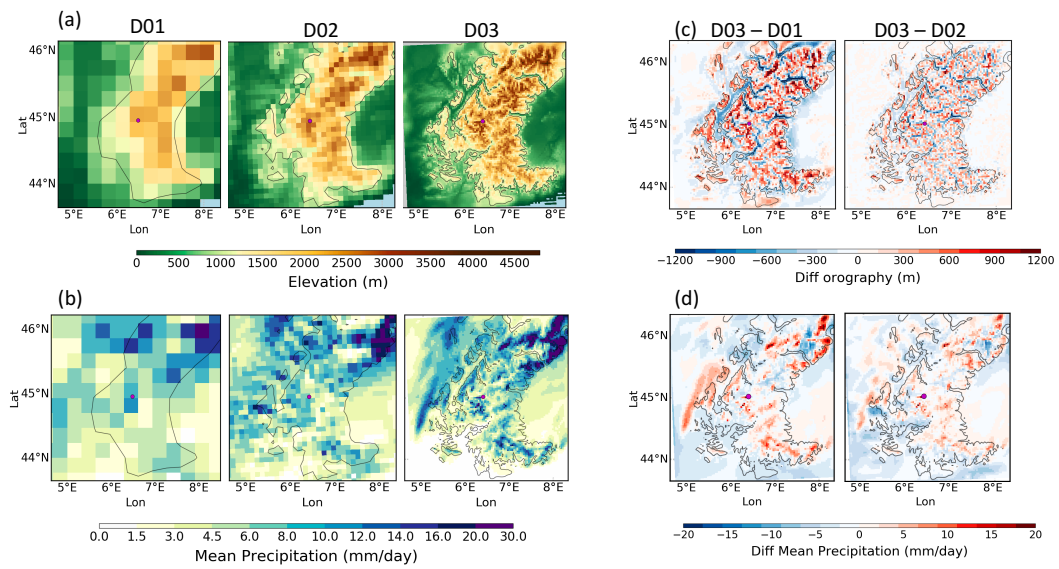


Figure 9. Orography (a) and accumulated predicted precipitation (b) from WRF-Chem at different resolutions during the event across the French Alps. Differences between the different resolutions/domains of orography and mean precipitation are shown at panels (c) and (d) accordingly. The black solid line represents the contour line at 1000 m altitude height. Purple dot depicts Col de Lautaret.

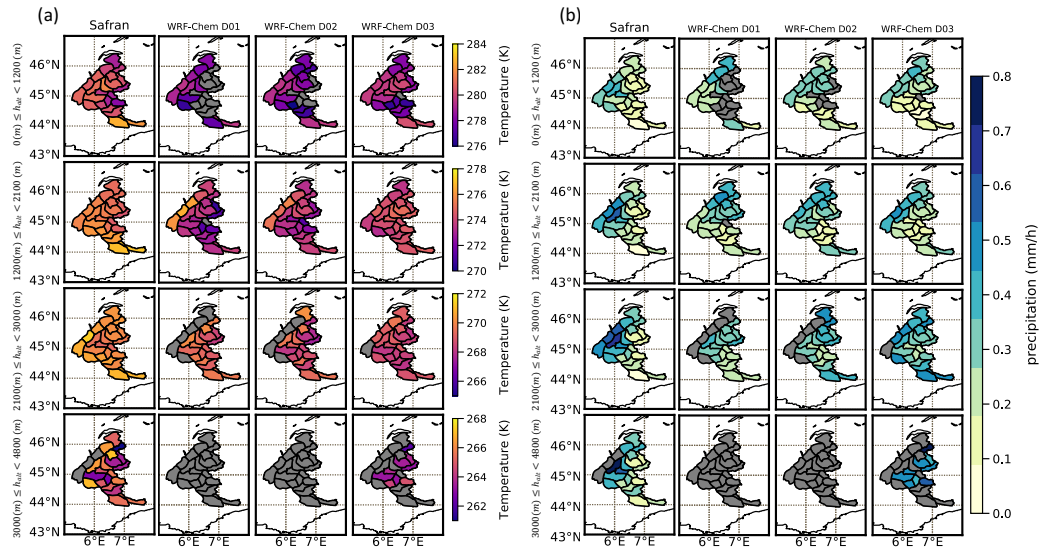


Figure 10. Spatial distribution of co-located binned SAFRAN (first column panels), WRF-D01 (second column panels), WRF-D02 (third column panels), WRF-D03 (fourth column panels), mean temperature - (a) , hourly precipitation (b) from 30 March to 3 April 2018. The first row represents data at altitudes (a.s.l.) below 1200 m, the second row above 1200 m and below 2100 m , the third row above 2100 m and below 3000 m and the fourth row 3000 m and above. Grey color indicates no data.

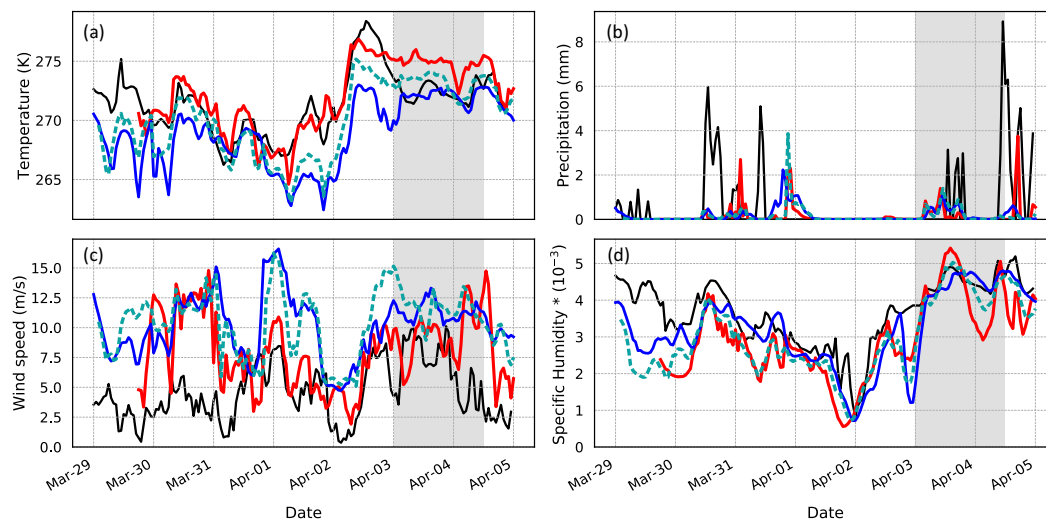


Figure 11. Plot of temperature at 2m height (a), 1h accumulated precipitation (b), and wind speed (c), specific humidity (d) measured during the 30 March and 4 April event at the Col du Lautaret site. WRF-Chem simulated values of D01, D02, D03 are depicted by colors blue, teal and red accordingly. Measurement values are illustrated with black color. Light gray shaded area corresponds to dust deposition event for the period 3 April and 4 April 12:00 UTC 2018.

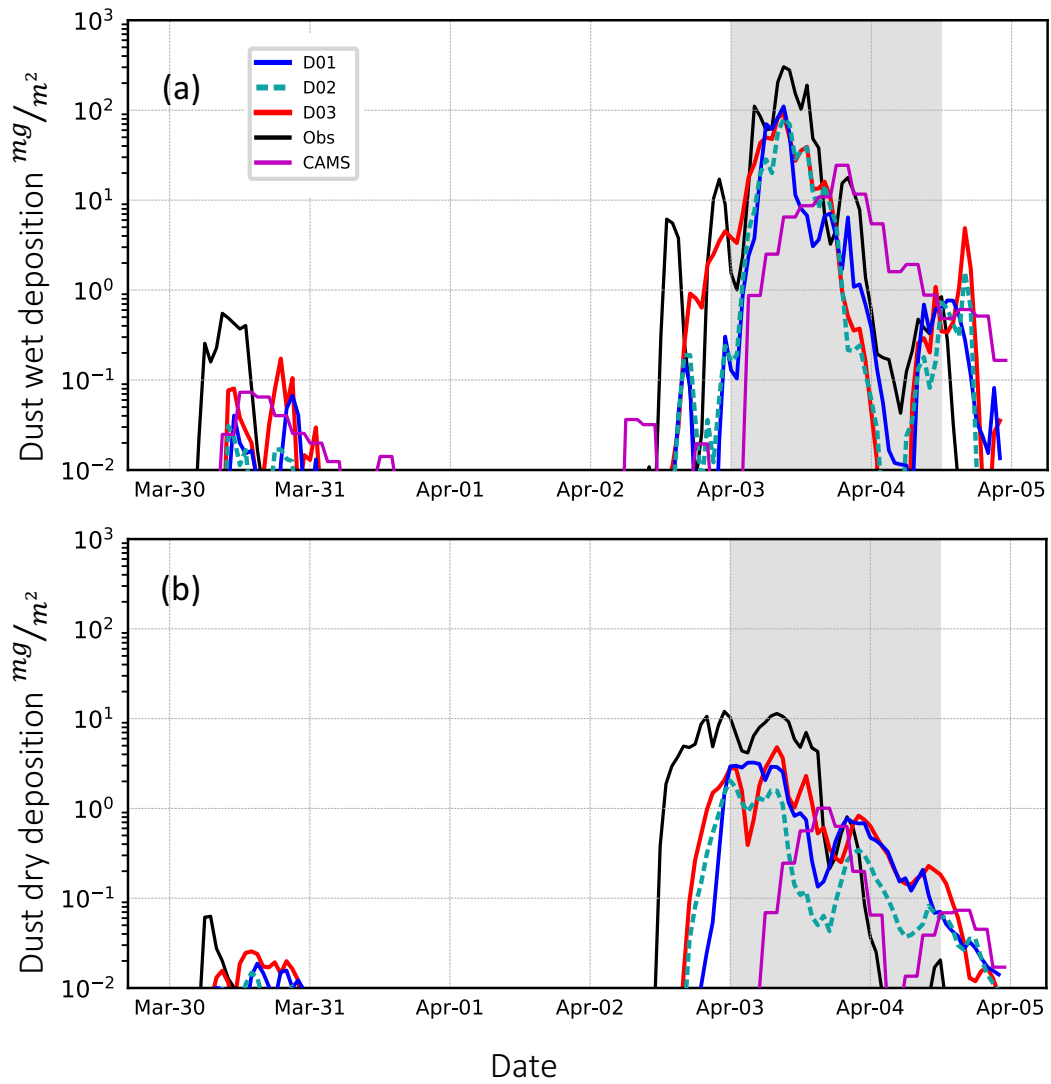


Figure 12. Model predicted 1h accumulated wet (a) and dry (b) deposition of dust at Col du Lautaret. WRF simulated values of D01, D02, D03 are depicted by colors blue, teal and red accordingly and CAMS reanalysis values by magenta. Aladin simulated values “corrected” by observations are illustrated with black color.

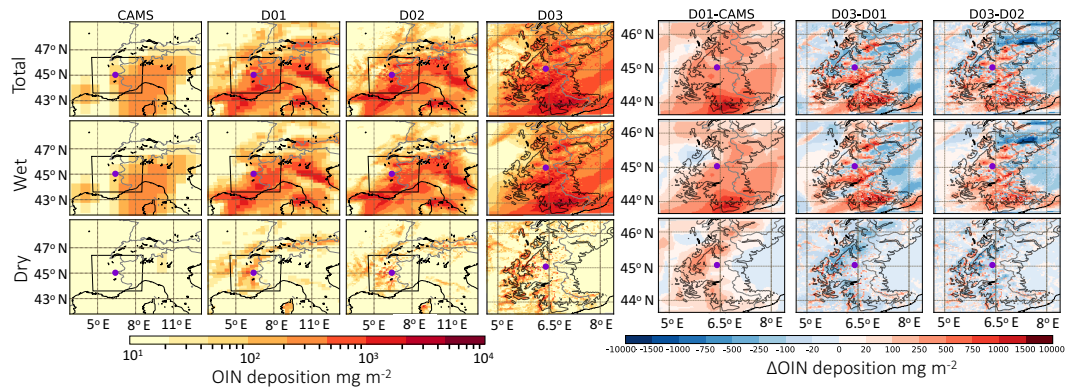


Figure 13. Accumulated dust from CAMS reanalysis and predicted OIN. Total (wet & dry) (first row panels) , wet (second row panels) and dry (third row panels) deposition across the Alps on 3 of April 2018. WRF-Chem D01 and CAMS values are depicted over the geographical limits of D02 in order to illustrate and compare the dust deposition rates over the Alpine region. CAMS values are shown on first column panels, WRF-Chem D01 are second column panels D02 are third column panels and D03 fourth column panels. Differences between D01 and CAMS as well as between D03 and D01 and D03 and D02 are shown at the fifth, sixth and seventh column panels accordingly. The inner black box at the first (CAMS) and second (D01) and third (D02) column panels represents the geographical limits of D03. The black solid line represents the contour line at 1000 m altitude height. Purple dot depicts Col du Lautaret.

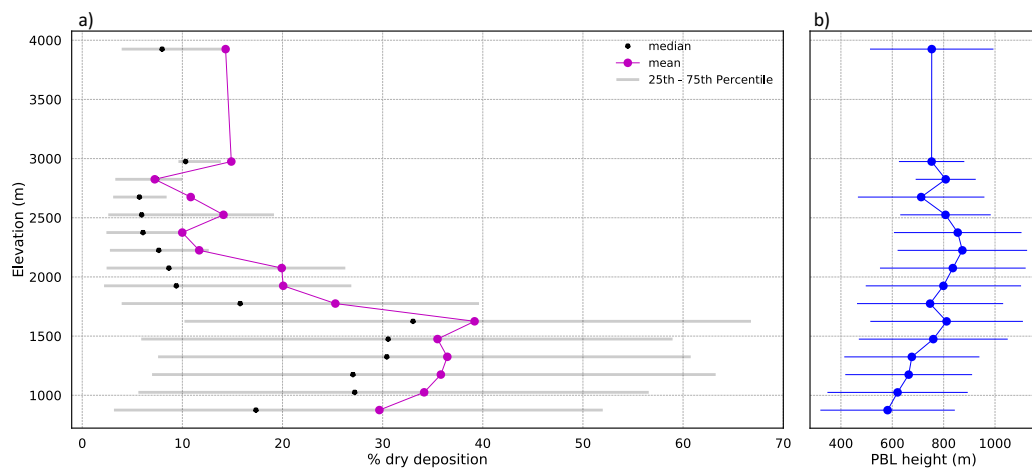


Figure 14. Altitude dependence of (a) the percentage dry to total modeled deposition; black asterisks represents the median and magenta dots the mean values, grey line depicts the 25th to 75th percentile intervals, (b) PBL height; blue line presents the standard deviation and shows the spatial variability in each elevation bin, from WRF-Chem D03 at the western French Alps (longitudes less than 6.5°E) on 3rd of April 2018. Deposition rates and PBL heights are binned at 150 m intervals from 800 to 3050 m, and the last bin includes the values above 3050 m.

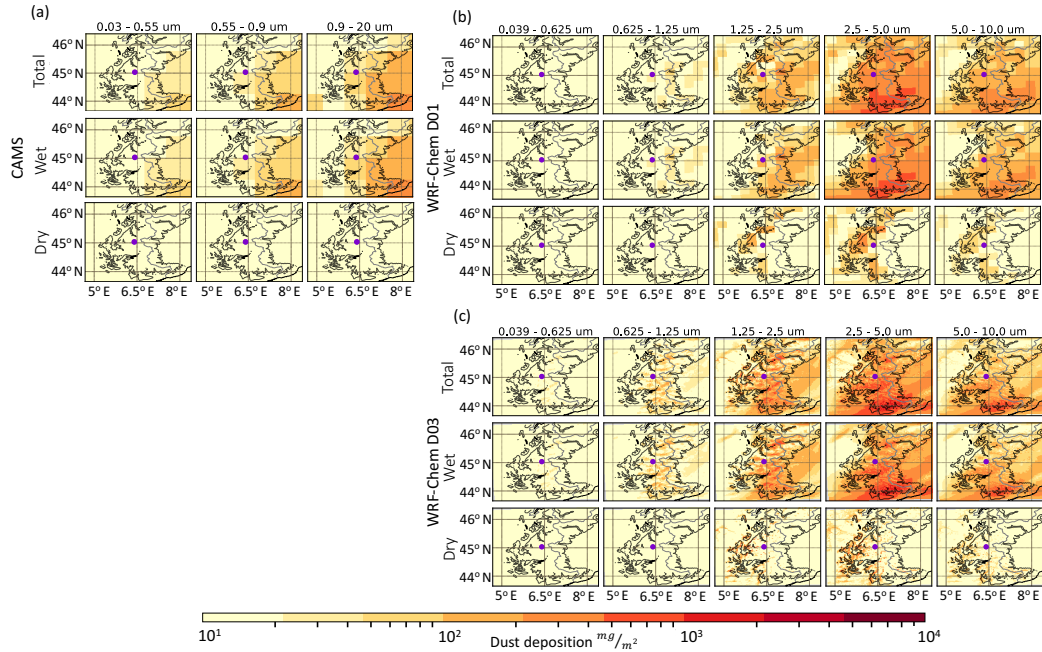


Figure 15. Accumulated dust from CAMS reanalysis and WRF-Chem OIN predicted total (wet & dry) (first row panels) , wet (second row panels) and dry (third row panels) deposition at different size bins across the Alps on 3 of April 2018. CAMS panel (a) and WRF-Chem D01 panel (b) and D03 panel (c) values are depicted over the geographical limits of WRF-Chem D03 in order to illustrate the dust deposition rates over the Alpine region. Size bin 0.039-0.625 μm includes the WRF-Chem D01 accumulated dust deposition rates from the first 4 size bins (0.039-0.078 μm , 0.078-0.156 μm , 0.156-0.312 μm , 0.312-0.625 μm). The black solid line represents the contour line at 1000m altitude height. Purple dot depicts Col du Lautaret.

Acknowledgments

IGE and CNRM-CEN are part of Labex OSUG@2020 (investissement d'avenir – ANR10 LABX56). This work was performed using HPC resources from GENCI-ID-RIS (Grant A007017141) and the IPSL mesoscale computing center (CICLAD: Calcul Intensif pour le CLimat, l'Atmosphère et la Dynamique). This study was supported by the Ecole Doctorale Terre Univers Environnement de Grenoble and part of it by Early Career Scientist Assembly (ECSA) FY2020 National Center for Atmospheric Research/Research Applications Laboratory (NCAR/RAL) sponsored by the National Science Foundation (NSF). This work was partly supported by Lautaret Garden – UMS 3370 (Univ. Grenoble Alpes, CNRS,SAJF, 38000 Grenoble, France), a member of AnaEE France (ANR-11-INBS- 0001 AnaEE-Services, Investissements d'Avenir frame) and of the eLTER European network (Univ. Grenoble Alpes, CNRS, LTSER Zone Atelier Alpes, 38000 Grenoble, France) and by ANR grant EBONI (ANR-16-CE01-0006). Marie Dumont has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 949516, IVORI). We acknowledge Institute of Environmental Geosciences (IGE) for administrative support. We acknowledge use of the WRF-Chem pre-processor tools provided by the Atmospheric Chemistry Observations and Modeling Lab (ACOM) of NCAR. We acknowledge NCAR ACOM for providing the WRF-Chem chemical boundary conditions used in this study. We acknowledge Meteo France for providing SAFRAN reanalysis data used in this study. We acknowledge the NASA/Goddard Space Flight Center's PMM Science

876 Team and PPS, which develop and compute the Integrated Multi-satellitE Retrievals as
 877 a contribution to GPM, and archived at the NASA GES DISC. We acknowledge the Emis-
 878 sions of atmospheric Compounds and Compilation of Ancillary Data (ECCAD) for pro-
 879 viding anthropogenic emissions used in this study. We thank the CAMS development
 880 and support teams at ECMWF for providing dust deposition rates used in this study.
 881 We thank B. Boudevillain and F.Tuzet for supporting this work by providing helpful in-
 882 formation for observation data used in this study.

883 Data Availability Statement

884 Col du Lautaret in situ measurements are available at <https://doi.org/10.18709/perscido.2020.09.ds330>.
 885 CAMS deposition fluxes data are available by contacting M.Parrington and/or J.Flemming
 886 by email (Mark.Parrington@ecmwf.int, Johannes.Flemming@ecmwf.int). The radar rain-
 887 fall mosaic data is available from <https://radarsmf.aeris-data.fr/>. The code used for this
 888 study is available on Zenodo <https://doi.org/10.5281/zenodo.5221694> .

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