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D8.5: Design of the AERO VRE characteristics

needed to implement atmospheric and aerosol data exploitation services, and

report documenting the algorithms and methods used for the AERO VRE [B7]

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1. INTRODUCTION

In the framework of ITINERIS WP8, a specific Virtual Research Environment (VRE) will be realized for exploiting and analysing atmospheric and, in particular, aerosol data linked to the Work Package 4 (WP4): Atmosphere.

The aim of the current deliverable is to describe the design of such VRE focused on the study of desert dust particles and aerosol typing. Both products are the results of the activities of the Task 4.11 of WP4 for which datasets are not yet available even if designed. Along with these products, additional products will be used for the purposes of the VRE enriching the possibilities for the researchers and users in general.

This document is structured in 2 main parts, one describing the desert dust tool and the other the aerosol typing one. The desert dust section is made of 3 subsections: i) an overview of the importance of desert dust particles and available information at the present over the Country; ii) a description of the tool for desert dust particles, with details on the datasets to be used and relevant information for the users; iii) a description of how the VRE will be implemented in D4Science frame (https://www.d4science.org/), and of how to access datasets and visualization routines. The aerosol typing part is organized in a similar way: i) an introduction on its relevance and current data availability; ii) the information to be visualized in the VRE and additional data extra RIs.

2. DESERT DUST

Desert dust particles are produced by wind erosion of arid and semi-arid surfaces. These mineral particles constitute a major component of atmospheric aerosol that affects climate, weather, ecosystems, and socio-economic sectors such as human health, transportation, solar energy, and air quality (Mona et al., 2023). To understand these impacts and increase the ability of affected countries to cope with them, a trustworthy and abundant collection of multi-platform dust measurements is essential. This is a key element for the improvement of the knowledge on dust with the needed spatio-temporal resolution. The large source regions are the deserts in Northern Africa as highlighted, for example, by Figure 1. Emitted in desertic regions, for example Saharan dust can travel over large distances reaching the Caribbean. The Mediterranean Basin is often affected by desert dust coming from Sahara, Sahel and occasionally from Arabian Peninsula (Mona et al., 2006; Mamouri et al., 2013). Due to climate change, the local aerosol load over the broader Mediterranean area is expected to increase in terms of mineral dust contribution. According to Gavrouzou, et al. (2021), the number of dust detection from satellite observations in the Mediterranean doubled in the 2005-2019 period and since 2020, strong dust intrusions over Europe are also been reported by international institutions as the WMO Barcelona Dust Regional Center, CAMS and EUMETSAT. This highlights the need of adaptation actions for the presence of sand and dust storms considering a broad regional perspective (i.e., including source but also long-range transported regions) and the requirement to build mitigation strategies considering local, regional but also global scales.

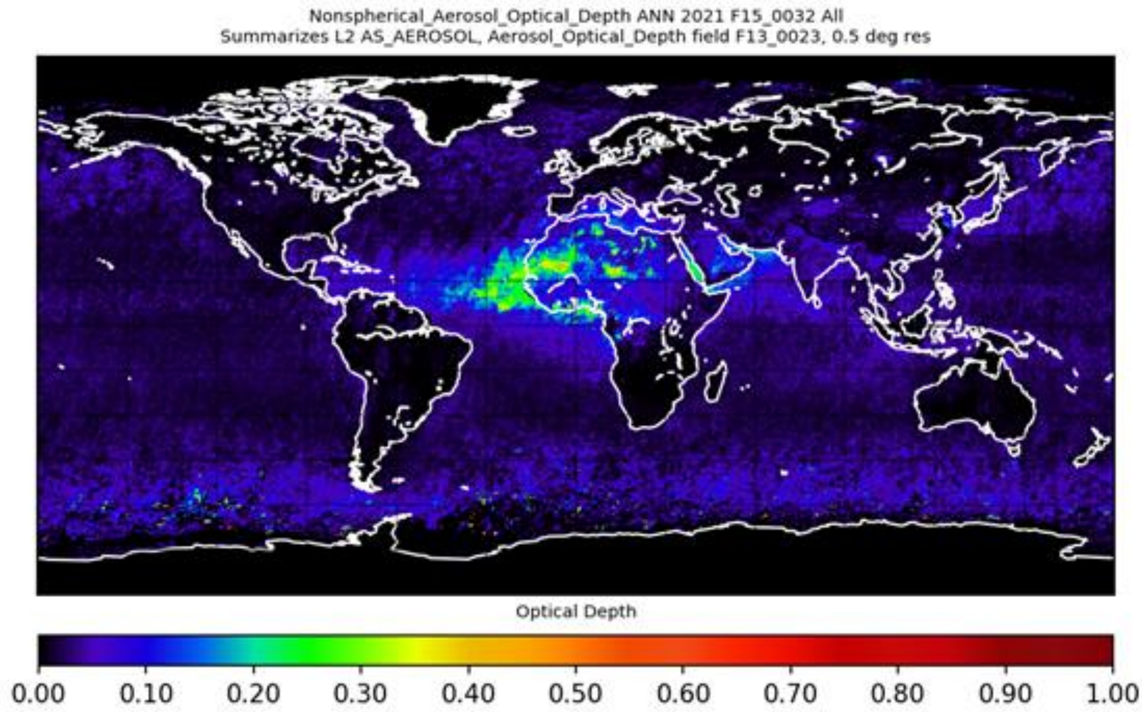

Figure 1: Mean annual Aerosol Optical Depth (AOD) related to non-spherical particles (i.e., dust), as measured by the Multi-angle Imaging SpectroRadiometer (MISR) in 2021 (https://l0dup05.larc.nasa.gov/L3Web)

Dust loads mainly affect the Central Mediterranean region, especially Italy, during spring and summer, while between November and January the dust activity is lower (Mona et al., 2006; Boselli et al., 2012; Gkikas et al., 2022). However, high-intensity dust events can occur in any season and last for several days with high dust loads in the free troposphere and near the ground. The amount of dust that reaches Italy can have significant effects on both the environmental and socio-economic sectors (Mallone et al., 2011; Barnaba et al., 2017; Di Mauro et al., 2019). Therefore, it is very important for scientists to better understand the processes and investigate the intensity, the duration and the variability of the dust events, in order to reduce their negative impacts.

2.1 Description of the VRE-AERO Desert dust tool

The aim of this tool is to provide reliable information on the atmospheric dust distribution over Italy along with its temporal variation, on various spatiotemporal scales, for at least the last 20 years. In general, there are plenty of datasets of dust products obtained from simulations or observations or from the combination of observations with dust models (reanalysis). A review of the available observational datasets about mineral dust is reported in Mona et al., (2023). Some of them provide exclusively data of dust optical and microphysical parameters, whereas others need to be combined in order to retrieve dust products. Each dataset has its own characteristics and advantages but also its own limitations. Model data are characterized always by uncertainty, whereas observations provide a limited spatiotemporal coverage, and their availability and quality are affected by weather conditions. In this tool a set of quality-assured and validated datasets will be used complementarily with the aim to identify and quantify the presence of dust in the atmosphere, overcoming possible gaps in observations or the uncertainty of the simulations.

In the following, we present the datasets that have been selected for the VRE-AERO DESERT DUST tool, considering specific requirements, namely: (i) The datasets should have sufficient geographical coverage over the entire country. (ii) The temporal domain of the datasets should span at least one decade within the last 20 years, thus, giving the possibility of future climatological studies (e.g., the investigation of dust cycle, seasonality, interannual variability and any potential trends). (iii) The dust parameters provided by the datasets should be appropriate for assessing the impacts of dust on socio-economic sectors. Moreover, they should provide information for the presence of dust both near the Earth's surface and in upper levels, such as dust optical depth (DOD), dust surface concentration, and dust extinction coefficient profiles. (iv) The data should be quality-assured and validated. (v) The data should be under open access policy.

The list of products that will be visualized in the VRE would not mean exhaustive of all available datasets, but they are representative for the description of spatio-temporal desert dust distribution. In the future other data in particular with very tiny spatial resolution as the ones available from EUMESAT platform and profiling information provided by EarthCARE could be added.

2.1.1 MONARCH dust regional reanalysis

The MONARCH (Multiscale Online Non-hydrostatic AtmospheRe CHemistry) dust regional reanalysis (fully described in Di Tomaso et al., 2022) represents state-of-the-art desert dust information over a domain covering the most prominent dust source areas in northern Africa and the Middle East. This dataset has been released for a 10-year period, spanning 2007 to 2016, over a spatial domain extending from 0 to 70° N latitude and from 30° W to 70° E longitude. MONARCH reanalysis novelty includes its unprecedented spatial and temporal resolution: Reanalysis fields are available at a 3-hourly time step, at a horizontal resolution of 0.1° latitude x 0.1° longitude (~ 10 km × 10 km at the Equator). The reanalysis has been obtained using the MONARCH model and by assimilating satellite coarse-mode DOD at 550 nm, derived from the MODerate resolution Imaging Spectroradiometer (MODIS) instrument operating aboard NASA's Aqua satellite. The MONARCH reanalysis dataset consists of upper-air profile variables such as dust mass concentration and an extinction coefficient at 550 nm, surface fields such as accumulated dust dry and wet deposition and mass surface concentration, and total column fields like instantaneous total column dust load, DOD, and coarse DOD (particle radius > 0.6 μm) at 550 nm. The quality of MONARCH reanalysis has been extensively evaluated in terms of DOD (Mytilinaios et al., 2023).

2.1.2 MODIS-based dust product: MIDAS

The MODIS total and coarse DOD used here is based on the recently developed ModIs Dust AeroSol (MIDAS) dataset (Gkikas et al., 2021). MIDAS combines quality-filtered aerosol optical depth (AOD) from MODIS instrument at swath level, along with DOD:AOD ratios provided by the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2), reanalysis to calculate the contribution of mineral dust particles to the overall AOD on the MODIS native grid. MIDAS coarse-mode DOD is also derived using the MERRA-2 DOD fraction and considers only particles with radius larger than 0.5 μm. MIDAS provides columnar daily total and coarse DOD at 550 nm at a fine spatial resolution (0.1° × 0.1°) over a 15-year period (2003–2017). MIDAS provides DOD retrievals over Italy every 1 to 2 days at around 13:30 local time (LT).

2.1.3 MISR dust product

The Multi-angle Imaging SpectroRadiometer (MISR) is an imaging instrument on board NASA's Terra satellite which has provided aerosol observations on a global scale since 2000 (Diner et al., 1998). The ability of MISR to perform measurements at nine different view angles enables it to distinguish between the non-spherical and spherical particles, making it possible to separate mineral dust aerosols from other aerosol components. Thus, the AOD fraction of the non-spherical particles can be considered equivalent to the DOD with relative certainty. In this study we will use the daily non-spherical AOD retrieval at 557.5 nm provided by the MISR Level 3 Component Global Aerosol Product (MIL3DAE; version

F15_0031) dataset, on a 0.5° × 0.5° spatial grid during the period 2000–2016. MISR passes over Italy at about 10:30 LT with a frequency of 7–9 days.

2.1.4 AERONET dust-filtered products

The AERONET (AErosol RObotic NETwork) ground-based photometer network provides a long-term and continuous database of high-quality aerosol optical properties globally since 1993. In this study, we will use AERONET Version 3 quality-assured data (i.e. level 2; Giles et al., 2019), i.e., the AOD and coarse AOD at 500 nm and the Ångström exponent (AE) at 440–870 nm. The AE is used as a filter because it is inversely related to the average aerosol size. Lower AE values (<1) indicate the significant presence of coarse-mode particles (e.g., desert dust), whereas higher AE values (>1) imply a large abundance of fine particles (e.g., biomass burning and urban aerosols). Here we will follow a discrimination method where DOD = AOD when AE < 0.75, and all data with AE > 1.2 are considered free of dust, i.e., DOD = 0. Finally, a mixed aerosol type is assumed when $0.75 \leq AE \leq 1.2$. Some studies have used even lower discrimination thresholds (e.g., AE < 0.6 or < 0.4) in an effort to obtain pure mineral dust conditions (Pérez et al., 2006). On the other hand, the coarse AOD (particle radius > 0.6 μm) can be assumed directly equivalent to DOD since coarse-mode AOD is mainly dominated by desert dust particles, and however sea-salt contribution and other coarse particle contributions are typically negligible during strong events. At this moment there are 25 AERONET sites across the country, well distributed from the south (Lampedusa) to the north (Bolzano) of Italy, providing a very sufficient geographical coverage. AERONET data are acquired at 15 min intervals on average, and this renders AERONET the dataset with the finest temporal resolution between the selected datasets.

2.1.5 ACTRIS/EARLINET dust product

EARLINET (European Aerosol Research LIdar NETwork) currently consists of more than 30 active lidar stations across Europe, providing daytime and night-time measurements of aerosol optical properties, twice per week on average, since 2000. The main products of an EARLINET lidar system are the aerosol backscatter and extinction coefficient profiles as well as the intensive properties that derive from them, namely the Ångström exponent (AE) and the lidar ratio (LR). In the frame of ITINERIS Task 4.11, a new desert dust data product is being designed using ACTRIS/EARLINET standard products, i.e., aerosol extinction and backscatter coefficient. The desert dust product consists of dust extinction and dust backscatter coefficient profiles (DEX and DBC, example in Figure 2) obtained combining particle depolarization ratio profiles and backscatter/extinction profiles available at the same time over ACTRIS/EARLINET stations. Such datasets will be retrieved as part of the activities of Task 4.11 of WP4 and provided through the ITINERIS Hub (WP2). Quality assured data (Level 2.0, QC 3.0; https://www.earlinet.org/index.php?id=293) will be used, obtained from 5 active EARLINET stations in Italy. Later, and if there are simultaneous lidar and photometer measurements at a station, it will also be possible to retrieve the dust mass concentration profile.

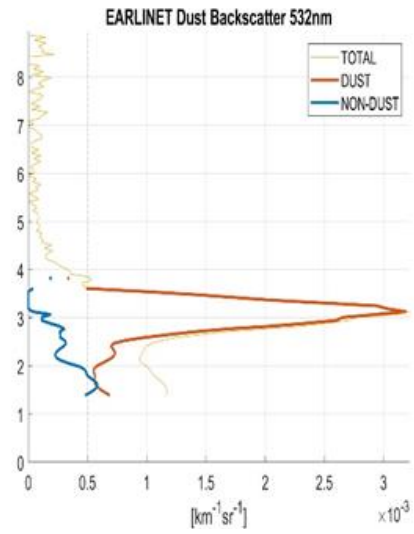

Figure 2: Example of a total aerosol backscatter coefficient profile (yellow) separated into its dust (red) and non-dust (blue) component.

2.1.6 WMO SDS-WAS Multi-Model dust product

The World Meteorological Organization (WMO) Barcelona Dust Regional Center delivers timely and high-quality sand and dust storm daily forecasts for Northern Africa, the Middle East, and Europe,. Every day 72h dust forecasts of DOD at 550 nm and dust surface concentration are available, provided by 15 individual dust models. The product that we will use here is called Multi-Model (ensemble) forecast and it is the median of all the individual dust forecasts for a particular day, after bi-linear interpolation to a common grid mesh of 0.5º × 0.5 (Basart et al., 2019; Terradellas et al., 2022). This product is available since 2012 and the output frequency is of 3 hours. In general, the Multi-Model forecast has shown better verification scores than any of the contributing models in most regions and time periods and is therefore considered a valuable tool to issue trust-worthy predictions of mineral dust in the domain served by the WMO Barcelona Center.

As it can be understood from the above, each dataset must be exploited differently according to the nature of the data it provides and its spatio-temporal characteristics, so that its depiction can be a tool for drawing useful conclusions about the atmospheric dust. For example, it is preferable to visualise columnar data (e.g., DOD) of fine spatial resolution and high spatial coverage provided by satellite, reanalysis and model datasets, as maps, while those measured at station level but with fine temporal resolution (e.g., AERONET), are preferable to be visualized as time series. Below an example is given of how a dust episode, which occurred over the Central Mediterranean region in the evening of April 4, 2016, can be investigated (Figure 3).

Figure 3 shows the DOD maps of the Multi-Model (left) and the MONARCH reanalysis (right) outputs at 21:00 UTC, whereas in the center the closest in time available MIDAS overpass is from one day before, that is why the dust plume is shifted towards east, compared to the position it had the next day. Here the MISR satellite-based DOD is not shown because no overpass is available on those dates. In Fig. 3 it is clear that a significant dust load originated in the Sahara Desert, was transported over the Mediterranean Sea and arrived in Central and Eastern Europe.

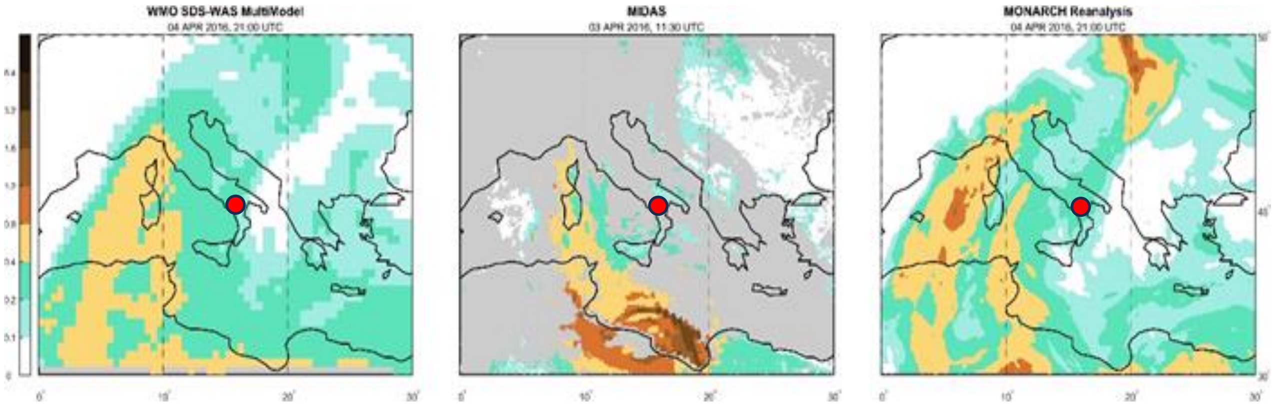

Figure 3: WMO SDS-WAS Multi-Model (left) and the MONARCH reanalysis (right) DOD on 4 April 2016 at 21:00 UTC, and MIDAS DOD (center) on 3 April 2016 at 11:30 UTC. The red dot denotes the CNR-IMAA site in Potenza, Italy (40.60° N, 15.72° E).

That night the ACTRIS/EARLINET lidar system of Potenza (red dot in Fig. 3) measured a dust profile where a significant dust layer between 2 and 4 km above sea level is apparent (Fig. 4). In the graph the two closest in time MONARCH reanalysis DEX profiles are plotted as well, which can also identify the dust layer. The MONARCH reanalysis profiles were collocated with the site coordinates, through bilinear interpolation.

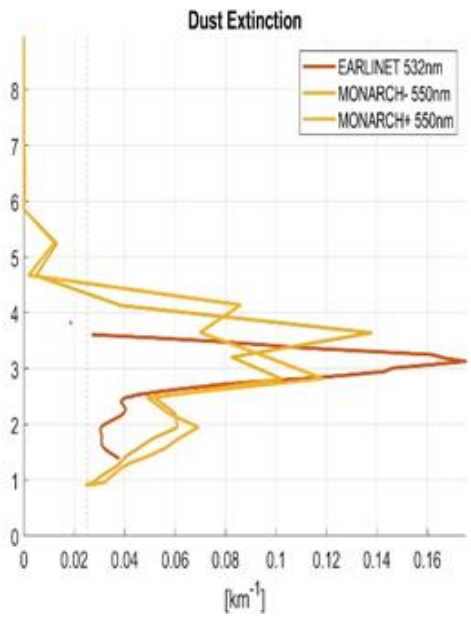

Figure 4: ACTRIS/EARLINET DEX profile (red) measured between 18:47 and 22:15 UTC and MONARCH reanalysis DEX output at 18:00 (yellow) and at 21:00 UTC (orange), over the EARLINET station at Potenza, on 4 April 2016.

Lastly, the time-series of the Ångström exponent and the coarse AOD from the AERONET site of Potenza along with the collocated DOD obtained from the Multi-Model, the MONARCH reanalysis and the MIDAS dataset through bilinear interpolation, are plotted in Fig. 5 centred around the time window of the EARLINET measurement (t1 = 18:47 – t2 = 22:15). AERONET measurements were performed outside the EARLINET window because the sun-photometer operates only during daytime; however, it is clear (Fig. 5) that within 12 hours prior to lidar measurement the AE was very low (< 0.4) and the coarse AOD at some point exceeded 0.4. Similarly, the Multi-Model, the MONARCH reanalysis and the MIDAS datasets managed to capture the temporal evolution of the phenomenon quite well.

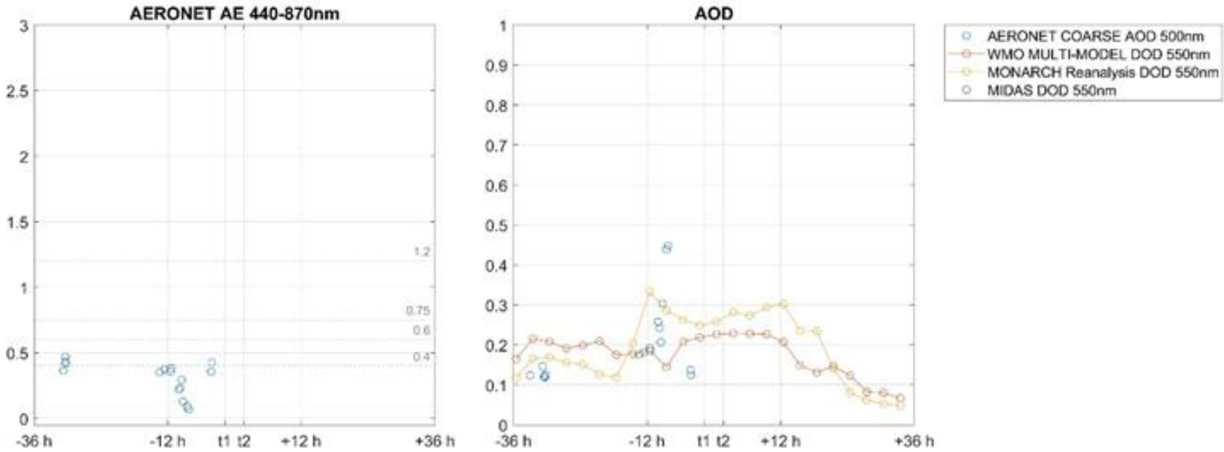

Figure 5: AERONET AE (left) and AERONET coarse AOD along with the WMO SDS-WAS Multi-Model, the MONARCH reanalysis and the MIDAS DOD (right), during a three-day period, centred around the EARLINET measurement (t1-t2), at the AERONET site of Potenza.

2.2 Desert dust tool implementation.

The Desert Dust visualization tool in the VRE will be implemented in the D4Science frame. In the workspace to be dedicated to VRE- AERO, DD section, all the datasets and routines for acting and elaborating data will be included. Following the general schema of the use of D4Science within he ITINERIS VRE, this will allow the access of the VRE-AERO in an environment shared with all the other VREs and in general within the ITINERIS HUB.

Modalities for the access to relevant datasets and routines are described below, although fine tunings will be carried on in the next few months for adapting them in the frame of Rstudio in D4Science.

2.2.1 Access to datasets

As mentioned previously, all datasets to be used for this tool should be under open access policy and freely available on the internet, even if in some cases an access request is needed to download most of them. In the following, we will explain how this data can be accessed.

MONARCH Reanalysis

The MONARCH reanalysis dataset is available at http://hdl.handle.net/21.12146/c6d4a608-5de3-47f6-a004-67cb1d498d98 (Di Tomaso et al., 2021). The files can be downloaded manually by choosing the variable and the date of interest. A username and a password are required which are provided on request. To enable the download of a specific variable data over a ten years period, a Matlab script was created (Annex 1). Files are netcdf files, that can be handle with many program languages like NCL, Panoply,Rstudio, Python and Matlab.

MIDAS

The MIDAS dataset can be easily downloaded directly from https://doi.org/10.5281/zenodo.4244106 (Gkikas et al., 2020). No registration is required. Files are netcdf files, that can be handle with many program languages like NCL, Panoply,Rstudio, Python and Matlab.

MISR

The MISR standard data products can be found at the Atmospheric Science Data Center (ASDC) Distributed Active Archive Center (DAAC) located at the NASA Langley Research Center (LaRC; https://asdc.larc.nasa.gov; NASA, 2024a). More specifically, the user should visit the MISR Direct Data Download area (https://asdc.larc.nasa.gov/data/MISR), search for the MIL3DAE collection and then download the data manually. A free registration is needed also here. Files are netcdf files, that can be handle with many program languages like NCL, Panoply,Rstudio, Python and Matlab.

AERONET

AERONET Version 3 data are available from the AERONET web site (https://aeronet.gsfc.nasa.gov; NASA, 2024b). The user should use the download tool (https://aeronet.gsfc.nasa.gov/new_web/webtool_aod_v3.html), choose the station of interest and then download the data manually by selecting the period, the product (AOD and AE), the level (2.0) and the format (All Points). No registration is required. Data are provided in ascii format.

ACTRIS/EARLINET

ACTRIS/EARLINET dust profiles are an outcome of the task 4.11 activities. Such product will be free and open available through the ITINERIS Hub and will be associated to a doi. Files are netcdf files, that can be handle with many program languages like NCL, Panoply, Rstudio, Python and Matlab.

Multi-Model

The daily dust forecasts of the multi-model are available in the WMO Barcelona Dust Regional Center web site (https://dust.aemet.es/products/data-download). For the purposes of the present work, we will use the "Public" data, which requires registration first. Inside the Public_Data folder, the MULTI_MODEL subfolder can be found where the files are ordered per year and month. After selecting a specific month, the user can access the list of the daily files that can be downloaded. When the user selects a specific file, the available download links appear. Alternatively, the download of all the available files can be done through the script provided in the Annex 1 (it runs in Matlab).

2.2.2 Visualization routines

The VRE-AERO DESERT DUST tool will give the user the option to visualize the information they want in two different ways: either with 2D maps like those in Fig. 3 or with profiles and time series like those in Fig. 4 and 5 for specific observational sites in Italy. The maps will be able to display dust products from the satellites and models, and in particular the DOD and the surface concentration of dust (the latter only for the MONARCH reanalysis and the Multi-Model datasets). The user will be able to choose between these two variables and set the date they are interested in as well as the coordinates (latitude and longitude) of the area they want to examine. At a later stage, climatological information of these products will also be available, such as monthly, seasonal and annual averages. An example routine to be used to produce DOD maps for a particular day is given in Annex 2.

Regarding the visualizations at station level, the user will be able to pick one of all the available sites in Italy, participating in the AERONET or/and ACTRIS/EARLINET networks. After selecting a specific date, the tool will show all available products for that date, but also for a day before and after it. These products could include dust extinction profiles obtained from MONARCH reanalysis and EARLINET (if the station is an EARLINET member) and DOD data from satellites, models and AERONET (if the station is an AERONET member). Annex 2 shows an example routine that displays the DOD data at the Potenza station.

3. AEROSOL TYPING

The aerosol type is one of the most highly sought-after parameters by aerosol data users. It is important for authorities to estimate the contribution of the different aerosol sources, but it is important even for researchers to investigate the impact on radiative budget of each of the aerosol types, and even the interaction of the aerosol type with water in the different phases (cloud formation, raining events and so on). The lidar technique allows for the estimation of the aerosol type in the vertical dimension. This means that the aerosol type is provided at different altitudes: lower troposphere (important for human health, air quality, and human activities as a whole), mid troposphere (important for the long range transport of particles and human activities – i.e., aviation), and upper troposphere and lower stratosphere (important for the radiation budget – e.g., volcanic aerosols).

3.1 Description of the VRE-AERO aerosol typing tool

The tool for the investigation of the aerosol type will primarily make use of datasets developed in WP4, that will be hosted and made available through the ITINERIS HUB. This dataset is not yet available, but it will be related to different aerosol typing methods and will be tested and validated over Italian RI observational sites. The datasets could be extended to the other available experimental sites equipped with the suitable instrumental set up. Such datasets will be provided following the community standards (NetCDF files and relevant metadata) and FAIR principles: data will contain all information needed to guarantee the full traceability of the data from the instrument setup to raw and higher processing level data.

Based on the assessment of the aerosol typing methodology, which is one of the objectives of WP4, datasets will be made available for some Italian measurement sites whenever their experimental set up allows for such investigation. For such sites, it will be possible through the VRE to visualize the aerosol type for a single case (discussed in more detail in the following), but also for a climatological analysis. For instance, pie charts with the percentage of the aerosol types observed at each site for each season, for each year and/or for different altitude range could be visualized. This info will be visualized together with the number of observations collected in the selected temporal period/altitude range. This is important information whenever observations are not performed continuously (quite common in the case of aerosol lidar measurements). Figures 6 and 7 report examples of the visualization concept.

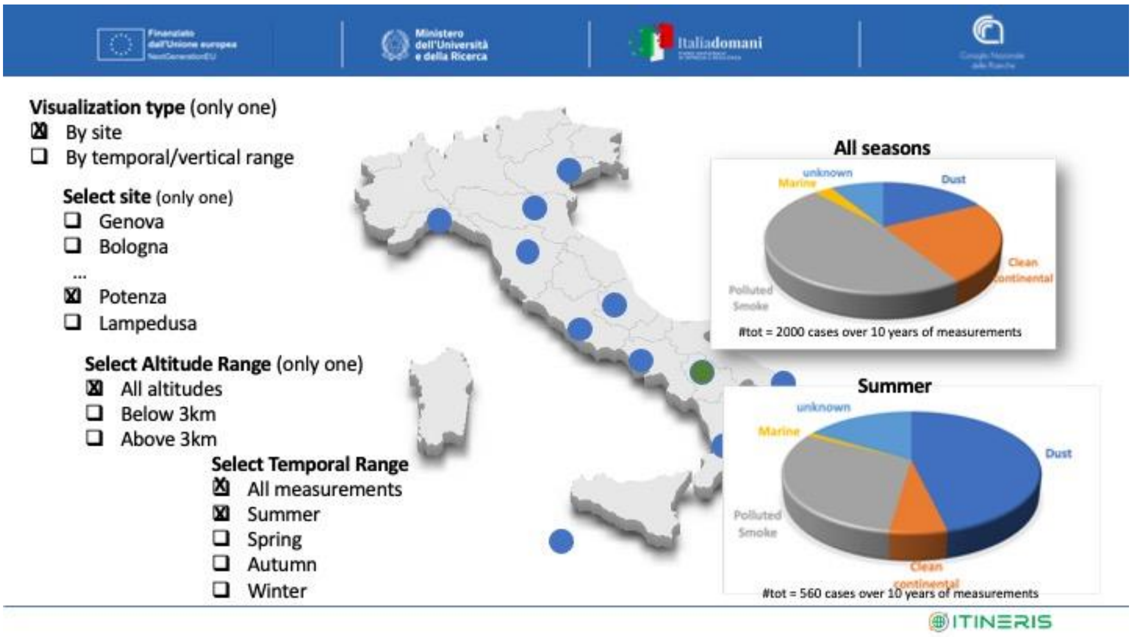

Figure 6: visualization idea for climatological analysis of the aerosol typing.

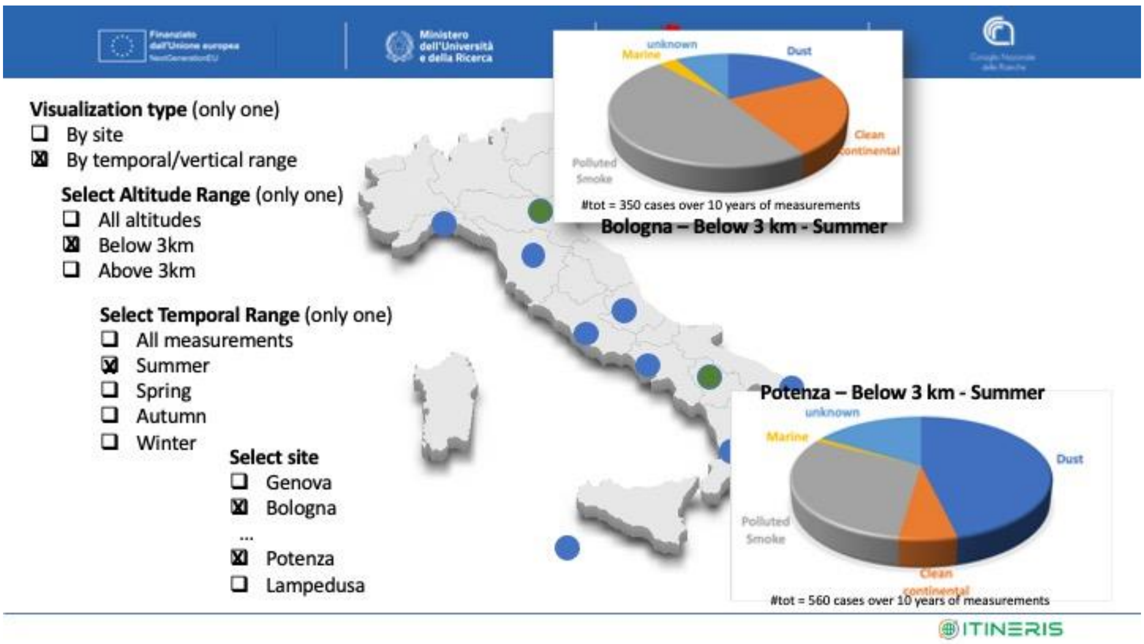

Figure 7: visualization idea for climatological analysis of the aerosol typing.

Differently, the single case investigation will make use of additional and external information. The concept behind this specific tool is the possibility to investigate specific cases using the aerosol typing output provided by ITINERIS but also some of the most relevant aerosol typing investigation tools currently available (e.g., backward trajectory analysis).

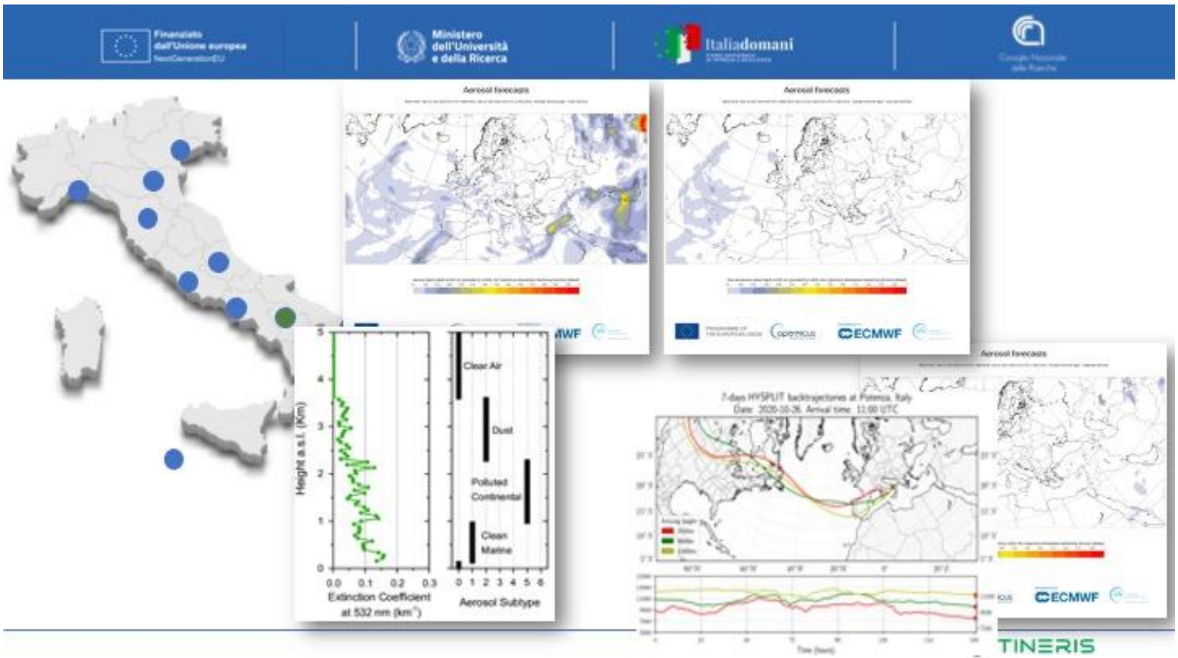

Figure 8: visualization idea or the aerosol typing single case investigation.

Here, similar to what has been developed for the desert dust investigation, the idea is to simultaneously visualize the aerosol typing output resulting from different approaches and datasets, providing an easy way for integrating non-uniform information, to validate the typing algorithm and, finally, identify potential cases where the typing is not straightforward and mixtures could be relevant for further investigations. For such kind of application, the VRE will visualize together with the typing product obtained by the WP4 activities,

also FLEXPART back-trajectories will be visualized as well with user input for the altitude range, offering more flexibility and further comparisons.

Additionally, CAMS model reanalysis for the examined case could be displayed on the same page: CAMS provides forecast of the aerosol load as total on the vertical column, but also split over 4 main species (dust, sea salt, biomass burning and sulphate aerosols). These 4 components are retrieved from the forecast model considering the sources as modelled in the aerosol module of CAMS forecast (considering available source inventories and source mechanisms in the case of desert dust) and meteorological forecast for the transport mechanisms.

In this way, lidar observations can be compared to 2D and 3D forecast maps, investigating therefore the study case in terms of spatial and vertical distribution and understanding the degree of reliability of the aerosol type as determined by the aerosol observations. This synergistic visualization tool could offer unprecedented insight into the aerosol typing investigation both for research and outreach.

3.2 Aerosol typing tool implementation.

As for the case of desert dust, the aerosol typing visualization tool in the VRE will be implemented in the D4Science frame. In the workspace to be dedicated to VRE-AERO, the aerosol typing section, all the datasets and routines will be included. Following the general schema of the use of D4Science within the ITINERIS VRE, this will allow access to the VRE-AERO in an environment common with all the other VREs and in general in the ITINERIS HUB.

Modalities for the access to relevant datasets and routines are described below, although fine tuning will be made in the next months for adapting them in the frame of Rstudio in D4Science.

For the climatological analysis, the VRE-AERO for aerosol typing will use the data provided by Task 4.11 that will be made free and openly available through the ITINERIS HUB and will be associated to DOI.

For the single case analysis, the VRE-AERO for aerosol typing will use the data listed in the following together with the description of how these are accessible:

ACTRIS/EARLINET data

ACTRIS/EARLINET data can be accessible at the ACTRIS data portal (currently under upgrade) and at EARLINET database website (https://data.earlinet.org/earlinet/), where a registration is needed. After logging in the user can choose the station of interest and then select the period, the level (2.0) and the quality control version (V3.0) under the "Advanced Search" tab.

CAMS global reanalysis (EAC4)

data freely available on the Copernicus website at the following link: https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4?tab=overview.

Using the variable Organic matter aerosol optical depth at 550 nm (kg kg-1) it is possible to monitor the transport of aerosols produced by forest fires across the globe with a time resolution of three hours.

Routine for accessing such data and visualizing an animation of such prediction is reported in ANNEX 3.

NOAA HYSPLIT Lagrangian backtrajectory model:

data are freely available on the NOAA website at the following link:

https://www.ready.noaa.gov/hypub-bin/trajasrc.pl

Hysplit trajectories are used to investigate the origin of on-site measured aerosols. An approach that considers a set of backtrajectories and not a single trajectory is preferred because this more correctly simulates the real behavior of air particles.

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ANNEX 1 – SCRIPTS FOR DOWNLOADING DATA (DESERT DUST)

MONARCH Reanalysis

```
options = weboptions('Username','username','Password','password');
```

```
% The path of the folder where the data will be saved
path_folder = 'path_folder';

% The path of the variable that we want to download
path_url =
'https://earth.bsc.es/thredds_dustclim/fileServer/monarch-
dustclim/3hourly/variable_name/';

% Arrays of all the available years, months and days
year = ["2006" "2007" "2008" "2009" "2010" "2011" "2012" "2013"
"2014" "2015" "2016"];
month = ["01" "02" "03" "04" "05" "06" "07" "08" "09" "10" "11"
"12"];
day = ["01" "02" "03" "04" "05" "06" "07" "08" "09" "10" "11" "12"
"13" "14" "15" "16" "17" "18" "19" "20" "21" "22" "23" "24" "25"
"26" "27" "28" "29" "30" "31"];

for i=1:length(year)

% The sum of the days for each month for normal and leap years
    if strcmp(etos(i),'2008') || strcmp(etos(i),'2012') ||
strcmp(etos(i),'2016')
        dayssum = [31 29 31 30 31 30 31 31 30 31 30 31];
    else
        dayssum = [31 28 31 30 31 30 31 31 30 31 30 31];
    end

    for j=1:length(month)
        for k=1:dayssum(j)
  date = year(i) + month(j) + day(k);
            file = ' variable_name' + date + '03_av_an.nc';
            url = path_url + file; filename = path_folder + file;
            out = websave(filename,url,options);

        end
    end
end
```

<u>WMO SDS-WAS Multi-Model</u>

```
options = weboptions('Username','username','Password','password');

% The path of the folder where the data will be saved
path_folder = 'path_folder';

% The path of the variable that we want to download
path_url = 'https://dust.aemet.es/thredds/ncss/dataRoot/MULTI-
MODEL/';

% Variables: DOD550 & SCONC
```

```
vars = 'var=OD550_DUST&var=SCONC_DUST';
% Lat/Lon Subset & Horizontal Stride (No Subset here!)
coord = 'horizStride=1';
% Time Stride
tims = 'timeStride=1';

% Arrays of all the available years, months and days
year = ["2012" "2013" "2014" "2015" "2016" "2017" "2018" "2019"
"2020" "2021" "2022" "2023" "2024"];
month = ["01" "02" "03" "04" "05" "06" "07" "08" "09" "10" "11"
"12"];
day = ["01" "02" "03" "04" "05" "06" "07" "08" "09" "10" "11" "12"
"13" "14" "15" "16" "17" "18" "19" "20" "21" "22" "23" "24" "25"
"26" "27" "28" "29" "30" "31"];


for i=1:length(year)

% The sum of the days for each month for normal and leap years
    if strcmp(year(i),'2008') || strcmp(year(i),'2012') ||
strcmp(year(i),'2016') || strcmp(year(i),'2020') ||
strcmp(year(i),'2024')
        dayssum = [31 29 31 30 31 30 31 31 30 31 30 31];
    else
        dayssum = [31 28 31 30 31 30 31 31 30 31 30 31];
    end

    for j=1:length(month)
        for k=1:dayssum(j)

% Set 24h time range from 12:00 UTC of the current day to 09:00 UTC
of the next day
            tstart = 'time_start=' + year(i) + '-' + month(j) + '-'
+ day(k) + 'T12%3A00%3A00Z';
            if k == dayssum(j) && j == length(month)
                tstop = 'time_end=' + year(i+1) + '-' + month(1) +
'-' + day(1) + 'T09%3A00%3A00Z';
            elseif k == dayssum(j)
                tstop = 'time_end=' + year(i) + '-' + month(j+1) +
'-' + day(1) + 'T09%3A00%3A00Z';
            else
                tstop = 'time_end=' + year(i) + '-' + month(j) + '-
' + day(k+1) + 'T09%3A00%3A00Z';
            end
            url = path_url + year(i) + '/' + month(j) + '/' +
year(i) + month(j) + day(k) + '_3H_MEDIAN.nc?' + vars + '&' + coord
+ '&' + tstart + '&' + tstop + '&' + tims + '&accept=netcdf4';

            file = year(i) + month(j) + day(k) + '_3H_MEDIAN.nc';
            filename = path_folder + file;
            out = websave(filename,url,options);
        end
    end
```

```
end
```

ANNEX 2 – VISUALIZATION ROUTINES (DESERT DUST)

Visualize 2D Maps on a given date

```
% SET A DATE
Date = "Date"; % Format: YYYYMMDD

% MIDAS
% longitude [degrees east]
LON_M2=ncread('E:\3_DOD\MIDAS\1_Version2_08-11-
2020\GRID_RESOLUTION_0.1\MODIS-AQUA-C061_AOD-and-DOD-V1-
GRID_RESOLUTION_0.1-Date.nc','Longitude');
LON_M1 = unique(round(LON_M2,1));
% latitude [degrees north]
LAT_M2=ncread('E:\3_DOD\MIDAS\1_Version2_08-11-
2020\GRID_RESOLUTION_0.1\MODIS-AQUA-C061_AOD-and-DOD-V1-
GRID_RESOLUTION_0.1-Date.nc','Latitude');
LAT_M1 = unique(round(LAT_M2,1));
% aerosol optical depth
DODmidas=ncread('E:\3_DOD\MIDAS\1_Version2_08-11-
2020\GRID_RESOLUTION_0.1\MODIS-AQUA-C061_AOD-and-DOD-V1-
GRID_RESOLUTION_0.1-Date.nc','Modis-total-dust-optical-depth-at-
550nm');


% MONARCH Reanalysis
% longitude [degrees east]
LONrea=ncread('E:\3_DOD\MIDAS\2_REMAP\od550du-
AV_an\MO_od550du_Date_av_an.nc','lon');
% latitude [degrees north]
LATrea=ncread('E:\3_DOD\MIDAS\2_REMAP\od550du-
AV_an\MO_od550du_Date_av_an.nc','lat');
% aerosol optical depth
f_od550du=ncread('E:\3_DOD\MIDAS\2_REMAP\od550du-
AV_an\MO_od550du_Date_av_an.nc','od550du');
f_od550du(f_od550du < 0)=NaN;
DODrea = f_od550du(:,:,1,7);


% WMO
% longitude [degrees east]
LON=ncread('E:\dust.aemet\BDRC_THREDDS_Public_Data-
MULTIMODEL\Date_3H_MEDIAN.nc','longitude');
LON=double(LON);
% latitude [degrees north]
LAT=ncread('E:\dust.aemet\BDRC_THREDDS_Public_Data-
MULTIMODEL\Date_3H_MEDIAN.nc','latitude');
LAT=double(LAT);
% aerosol optical depth
f_od550du=ncread('E:\dust.aemet\BDRC_THREDDS_Public_Data-
MULTIMODEL\Date_3H_MEDIAN.nc','OD550_DUST');
DODwmo = f_od550du(:,:,4);
```

```
% Set colourbar non-linear scale
B = [0 .1 .2 .4 .8 1.2 1.6 3.2 6.4];

% % % % ---- COLOURMAP ---- % % % %
rgbDUST = (1      1      1;
0.6314     0.9294     0.8902;
0.3608     0.8902     0.7294;
0.9882     0.8431     0.4588;
0.8549     0.4471     0.1882;
0.6196     0.3843     0.1490;
0.4431     0.2863     0.1294;
0.2235     0.1451     0.0667;
0.1137     0.0745     0.0353);

T = 1:length(B)+1; limits = [T(1) T(end)];

figure(1)
set(gcf, 'Position', [1 41 1920 963]);
t = tiledlayout(1,3,'TileSpacing','compact','Padding','compact');

nexttile % WMO SDS-WAS MULTIMODEL
[NZ] = normalize_colorbar(B, DODwmo); NZ(isnan(DODwmo)) = NaN; NZ =
NZ';
pcolorm_normal(LAT, LON, NZ, 3, rgbDUST, limits); title('WMO SDS-
WAS MultiModel','FontSize',13);

c = colorbar; c.Location = 'westoutside'; c.Ticks=T(1:end-1);
c.TickLabels=B(1:end); c.LineWidth=1;

nexttile % MIDAS
[NZ] = normalize_colorbar(B, DODmidas); NZ(isnan(DODmidas)) = NaN;
NZ = NZ';
pcolorm_normal(LAT_M1, LON_M1, NZ, 3, rgbDUST, limits);
title('MIDAS','FontSize',13);

nexttile % MONARCH Reanalysis
[NZ] = normalize_colorbar(B, DODrea); NZ(isnan(DODrea)) = NaN; NZ =
NZ';
pcolorm_normal(LATrea, LONrea, NZ, 4, rgbDUST, limits);
title('MONARCH Reanalysis','FontSize',13);
```

Visualize DOD data at Potenza station on a given date

```
% LOAD AERONET-POTENZA AE_440-870 TIME-SERIES
load('E:\AERONET\AERONET_2004-2023_L2_All_POT_AE_AOD.mat',
'AE_440_870', 'DATETIME_all')
ts_aero_aeDT = DATETIME_all; ts_aeroAE = AE_440_870;
% Remove AE_440-870 = NaN
```

```
ts_aero_aeDT = ts_aero_aeDT(~isnan(ts_aeroAE)); ts_aeroAE =
ts_aeroAE(~isnan(ts_aeroAE));

% LOAD AERONET-POTENZA COARSE_AOD_500 TIME-SERIES
load('E:\AERONET\AERONET_2004-2023_ONEILL_L2_All_POT_COARSE.mat',
'CAOD_500', 'DATETIME_all')
ts_aero_coDT = DATETIME_all; ts_aeroCO = CAOD_500;
% Remove COARSE_AOD_500 = NaN
ts_aero_coDT = ts_aero_coDT(~isnan(ts_aeroCO)); ts_aeroCO =
ts_aeroCO(~isnan(ts_aeroCO));

% LOAD WMO SDS-WAS MUTLIMODEL-POTENZA DOD_550 TIME-SERIES
load('E:\dust.aemet\mat\MULTIMODEL_od550du_2012-202204.mat', 'DOD',
'dt_12_22_3h')
ts_modelDT = dt_12_22_3h; ts_modelDOD = DOD;

% LOAD MONARCH REANALYSIS-POTENZA DOD_550 TIME-SERIES
load('E:\4_REANALYSIS\3hourly_interpolated_points\MONARCH_Reanalysi
s_od550du_IMAAPZ_2007-2016', 'DODav', 'dt_07_16_3h')
ts_monarchDT = dt_07_16_3h; ts_monarchDOD = DODav;


% SET A DATE
Date = "Date"; % Format: YYYY-MM-DD
DT = datetime(Date+ " 12:00:00");

dt_start = DT - days(1.5); dt_end = DT + days(1.5);
inaero_aeDT = find(ts_aero_aeDT>=dt_start & ts_aero_aeDT<=dt_end);
% AERONET AE_440_870
inaero_coDT = find(ts_aero_coDT>=dt_start & ts_aero_coDT<=dt_end);
% AERONET Coarse_AOD_500
inmodelDT = find(ts_modelDT>=dt_start & ts_modelDT<=dt_end); %
MULTI-MODEL DOD_550
inmonarchDT = find(ts_monarchDT>=dt_start & ts_monarchDT<=dt_end);
% MONARCH Reanalysis DOD_550

%% PLOTS
figure(1)
set(gcf, 'Position', [177 383 1394 532]);
t = tiledlayout(1,2,'TileSpacing','compact','Padding','compact');
title(t,Date,'FontSize',15,'FontWeight','Bold')

nexttile % AERONET AE_440-870
if ~isempty(inaero_aeDT)
    plot(ts_aero_aeDT(inaero_aeDT), ts_aeroAE(inaero_aeDT),"o")
    hold on
    yline([.4 .6 .75 1.2],'--
',{'0.4','0.6','0.75','1.2'},'Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
```

```
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
end
grid on; ylim([-.05 3]); title('AERONET AE 440-870nm')
ax = gca; ax.FontSize = 13; pbaspect([1 1 1])

nexttile % COARSE AOD & DOD
% AERONET
if ~isempty(inaero_coDT) && isempty(inmodelDT) &&
isempty(inmonarchDT)
    plot(ts_aero_coDT(inaero_coDT),
ts_aeroCO(inaero_coDT),"o",'Color',[0 .447 .741])
    hold on
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'AERONET COARSE AOD
500nm',''},'Location','bestoutside')
end

% MULTI-MODEL
if isempty(inaero_coDT) && ~isempty(inmodelDT) &&
isempty(inmonarchDT)
    plot(ts_modelDT(inmodelDT),
ts_modelDOD(inmodelDT),'Marker','o','Color',[.85 .325 .098])
    hold on
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'WMO MULTI-MODEL DOD
550nm',''},'Location','bestoutside')
end

% MONARCH
if isempty(inaero_coDT) && isempty(inmodelDT) &&
~isempty(inmonarchDT)
    plot(ts_monarchDT(inmonarchDT),
ts_monarchDOD(inmonarchDT),'Marker','o','Color',[.929 .694 .125])
    hold on
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
```

```
    legend({'MONARCH Reanalysis DOD
550nm',''},'Location','bestoutside')
end

% AERONET + MULTI-MODEL
if ~isempty(inaero_coDT) && ~isempty(inmodelDT) &&
isempty(inmonarchDT)
    plot(ts_aero_coDT(inaero_coDT),
ts_aeroCO(inaero_coDT),"o",'Color',[0 .447 .741])
    hold on
    plot(ts_modelDT(inmodelDT),
ts_modelDOD(inmodelDT),'Marker','o','Color',[.85 .325 .098])
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'AERONET COARSE AOD 500nm','WMO MULTI-MODEL DOD
550nm',''},'Location','bestoutside')
end

% AERONET + MONARCH
if ~isempty(inaero_coDT) && isempty(inmodelDT) &&
~isempty(inmonarchDT)
    plot(ts_aero_coDT(inaero_coDT),
ts_aeroCO(inaero_coDT),"o",'Color',[0 .447 .741])
    hold on
    plot(ts_monarchDT(inmonarchDT),
ts_monarchDOD(inmonarchDT),'Marker','o','Color',[.929 .694 .125])
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'AERONET COARSE AOD 500nm','MONARCH Reanalysis DOD
550nm',''},'Location','bestoutside')
end

% MULTI-MODEL + MONARCH
if isempty(inaero_coDT) && ~isempty(inmodelDT) &&
~isempty(inmonarchDT)
    plot(ts_modelDT(inmodelDT),
ts_modelDOD(inmodelDT),'Marker','o','Color',[.85 .325 .098])
    hold on
    plot(ts_monarchDT(inmonarchDT),
ts_monarchDOD(inmonarchDT),'Marker','o','Color',[.929 .694 .125])
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
```

```
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'WMO MULTI-MODEL DOD 550nm','MONARCH Reanalysis DOD
550nm',''},'Location','bestoutside')
end

% AERONET + MULTI-MODEL + MONARCH
if ~isempty(inaero_coDT) && ~isempty(inmodelDT) &&
~isempty(inmonarchDT)
    plot(ts_aero_coDT(inaero_coDT),
ts_aeroCO(inaero_coDT),"o",'Color',[0 .447 .741])
    hold on
    plot(ts_modelDT(inmodelDT),
ts_modelDOD(inmodelDT),'Marker','o','Color',[.85 .325 .098])
    plot(ts_monarchDT(inmonarchDT),
ts_monarchDOD(inmonarchDT),'Marker','o','Color',[.929 .694 .125])
    yline(.1,'--','Color',[.5 .5 .5])
    hold off
    xlim([dt_week_start dt_week_end]);
    xticks([dt_week_start, t_b0355DT.Datetime - days(.5),
t_b0355DT.Start, t_b0355DT.Stop, t_b0355DT.Datetime + days(.5),
dt_week_end]);
    xticklabels({'-36 h','-12 h','t1','t2','+12 h','+36 h'})
    legend({'AERONET COARSE AOD 500nm','WMO MULTI-MODEL DOD
550nm','MONARCH Reanalysis DOD 550nm',''},'Location','bestoutside')
end
grid on; ylim([0 1]); title('AOD')
ax = gca; ax.FontSize = 13; pbaspect([1 1 1])
```

ANNEX 3 – ACCESS AND VISUALIZATION ROUTINE (AEROSOL TYPING)

```
Import netCDF4 as nc
import matplotlib.pyplot as plt
import matplotlib.animation as animation
import matplotlib.colors as colors
import cartopy.crs as ccrs
from PIL import Image

# Apri il file NetCDF in modalità lettura
file_path =
'C:/Users/Utente/Desktop/corso_py/adaptor.mars.internal-
1702915881.4971418-30197-10-5b4c6027-4956-434f-a9da-
18148738a7bd.nc'
dataset = nc.Dataset(file_path, 'r')

# Estrai le variabili di latitudine e longitudine
latitudes = dataset.variables['latitude'][:]
longitudes = dataset.variables['longitude'][:]

# Estrai i dati da una variabile specifica (ad esempio,
'omaod550')
aerosol_data = dataset.variables['omaod550'][70:, :, :]

# Inserisci manualmente le date nel formato desiderato
dates = ["20201014 21:00 ", "20201015 00:00", "20201014 21:00
", "20201015 00:00", "20201015 03:00", "20201015 06:00 ",
"20201015 09:00", "20201015 12:00", "20201015 15:00 ",
"20201015 18:00", "20201015 21:00", "20201016 00:00 ",
"20201016 03:00", "20201016 06:00 ", "20201016 09:00",
"20201016 12:00", "20201016 15:00 ", "20201016 18:00",
"20201016 21:00", "20201017 00:00 ", "20201017 03:00",
"20201017 06:00 ", "20201017 09:00", "20201017 12:00",
"20201017 15:00 ", "20201017 18:00", "20201017 21:00",
"20201018 00:00 ", "20201018 03:00", "20201018 06:00 ",
"20201018 09:00", "20201018 12:00", "20201018 15:00 ",
"20201018 18:00", "20201018 21:00", "20201019 00:00 ",
"20201019 03:00", "20201019 06:00 ", "20201019 09:00",
"20201019 12:00", "20201019 15:00 ", "20201019 18:00",
"20201019 21:00", "20201020 00:00 ","20201020 03:00",
"20201020 06:00 ", "20201020 09:00", "20201020 12:00",
"20201020 15:00 ", "20201020 18:00", "20201020 21:00",
"20201020 00:00 ", "20201021 03:00", "20201021 06:00 ",
"20201021 09:00", "20201021 12:00", "20201021 15:00 ",
"20201021 18:00", "20201021 21:00", "20201022 00:00 ",
"20201022 03:00", "20201022 06:00 ", "20201022 09:00",
"20201022 12:00", "20201022 15:00 ", "20201022 18:00",
```

```
"20201022 21:00", "20201023 00:00 ","20201023 03:00",
"20201023 06:00 ", "20201023 09:00", "20201023 12:00",
"20201023 15:00 ", "20201023 18:00", "20201023 21:00",
"20201024 00:00 ", "20201024 03:00", "20201024 06:00 ",
"20201024 09:00", "20201024 12:00", "20201024 15:00 ",
"20201024 18:00", "20201024 21:00", "20201025 00:00 " ,
"20201025 03:00", "20201025 06:00 ", "20201025 09:00",
"20201025 12:00", "20201025 15:00 ", "20201025 18:00",
"20201025 21:00", "20201026 00:00 ", "20201026 03:00",
"20201026 06:00 ", "20201026 09:00", "20201026 12:00",
"20201026 15:00 ", "20201026 18:00", "20201026 21:00",
"20201027 00:00 ""20201027 03:00", "20201027 06:00 ",
"20201027 09:00", "20201027 12:00", "20201027 15:00 ",
"20201027 18:00", "20201027 21:00", "20201028 00:00 ",
"20201028 03:00", "20201028 06:00 ", "20201028 09:00",
"20201028 12:00", "20201028 15:00 ", "20201028 18:00",
"20201028 21:00" ]  # Inserisci tutte le date necessarie

# Numero di istanti temporali
num_time_steps = aerosol_data.shape[0]

# Limiti personalizzati della scala logaritmica
vmin_custom = 0.05  # Modifica questo valore in base alle tue
esigenze
vmax_custom = 0.25  # Modifica questo valore in base alle tue
esigenze

# Creazione della mappa utilizzando cartopy e matplotlib
fig, ax = plt.subplots(subplot_kw={'projection':
ccrs.PlateCarree()})
c = ax.pcolormesh(longitudes, latitudes, aerosol_data[0, :,
:], shading='auto', cmap='Reds', vmin=vmin_custom,
vmax=vmax_custom)
ax.coastlines()

# Coordinate per Nord America ed Europa
north_america_extent = [-150, -30, 0, 80]  # [lon_min,
lon_max, lat_min, lat_max]
europe_extent = [-30, 60, 35, 70]  # [lon_min, lon_max,
lat_min, lat_max]

# Unione delle coordinate di entrambe le regioni
combined_extent = [
    min(north_america_extent[0], europe_extent[0]),
    max(north_america_extent[1], europe_extent[1]),
    min(north_america_extent[2], europe_extent[2]),
    max(north_america_extent[3], europe_extent[3])
]
```

```
# Impostazione dei limiti dell'asse x e y per includere
entrambe le regioni
ax.set_xlim(combined_extent[0], combined_extent[1])
ax.set_ylim(combined_extent[2], combined_extent[3])

# Aggiunta di una barra laterale per la legenda
cb = plt.colorbar(c, label='')

# Funzione di aggiornamento per l'animazione
def update(frame):
    c.set_array(aerosol_data[frame, :, :].flatten())

    # Estrai la data corrispondente al frame
    current_date = dates[frame]

    # Formatta la data con un formato comprensibile (puoi
personalizzare il formato)
    formatted_date = f"{current_date[:4]}-
{current_date[4:6]}-{current_date[6:]}"

    # Aggiornamento del titolo con la descrizione e la data
    ax.set_title(f'Organic Matter Aerosol Optical Depth at
550 nm - {formatted_date}', fontsize=9)

    return c,

# Nome del file di output con estensione .gif
output_file_gif =
'C:/Users/Utente/Desktop/corso_py/aerosol_animation.gif'

# Creazione dell'animazione
ani = animation.FuncAnimation(fig, update,
frames=num_time_steps, interval=200, blit=False,
repeat=False)

# Mostra l'animazione a video
plt.show()

# Salva l'animazione come file GIF
ani.save(output_file_gif, writer='pillow', fps=5, dpi=300)



# Chiudi il dataset
dataset.close()
```