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Understanding Mineral Dust Through a Doctoral Alliance †

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Abstract

We present an example of how a doctoral network can bring together multidisciplinary expertise and novel scientific advances in atmospheric dust. This network (Dust-DN) has started operations and is a strategic alliance of high-profile partners, able to leverage unique facilities for atmospheric research and innovative space missions. The network aims to improve our understandings of dust processes and microphysics, identify the signature of source regions, address the socio-economic impacts of dust transport and improve the quantification of the role of dust in the climate system. The first results have already been achieved and are shown here, and many more are expected to follow.

Keywords: dust; microphysics; source regions; climate; socio-economic impacts; environmental health; Earth observations; airborne research; remote sensing

1. Introduction

Mineral dust is a major atmospheric aerosol, and it represents one of the most visible and detectable aspects of transboundary transport of atmospheric constituents, impacting visibility, radiation and climate [1]. What are less evident are the quantitative impacts of dust on health, transportation and energy production. Atmospheric dust is not fully understood at the fundamental level (microphysical properties, dust emissions and source regions), and therefore, atmospheric models fail to fully reproduce its impacts. Moreover, dust observations using ground-based instrumentation, remote sensing and aircraft are abundant, but not evenly distributed; in particular, they are missing near major dust sources. The techniques and methodologies used to study dust are still under development, with each giving a different picture of this phenomenon with multiple facets. For example, it is now known that super-coarse and giant dust particles [2] have gone undetected for a long time due to limitations in the measurement and modelling tools that have been in use for decades, and this misdetection alters the understanding and the prediction of a number of processes. Finally, dust affects the environment, society and several economic sectors, with impacts, for example, on the transportation and energy sectors, the nature and cost of which are not fully understood and quantified. Several methodologies exist to study mineral dust, each giving its own differing picture of a complex phenomenon: numerical modelling, remote sensing, in situ observations and laboratory research.

2. Methodology

To address some of these challenges, the first doctoral network on a European scale (to our knowledge), researching the topic of atmospheric dust, is now active, bringing together expertise on mineral dust in the atmosphere and combining multidisciplinary aspects. The Dust Doctoral Network (Dust-DN) is a strategic international, interdisciplinary and intersectoral alliance of high-profile partners, able to leverage unique state-of-the-art facilities and recent innovative spaceborne missions; see Table 1. The network comprises dedicated applied research projects, with direct contributions and impacts embedded within the societal and industrial sector.

Table 1. Scientific facilities and spaceborne missions that Dust-DN can benefit from. Mod=modelling; IS=atmospheric in situ observations; RS=atmospheric remote sensing; Lab=laboratory; En=energy production facility.

Facility	Methodology	Operator
Marenostrum 5 HPC with MONARCH + EC-EARTH model	Mod	BSC
Cyclone HPC with WRF-Chem model	Mod	CyI
HoreKa HPC with ICON-ART model	Mod	KIT
Unmanned Systems Research Laboratory	Airborne IS	CyI
Cyprus Atmospheric Observatory	RS + IS	CyI
Panhellenic Geophysical Observatory of Antikythera	RS	NOA
Electron Microscopy Center	Lab	TUDa
Particle Settling Laboratory	Lab	UoR
Solar rad. and aerosol meas. facilities (incl. GAW PFR network)	RS	PMODWRC
Concentrating technologies and solar energy generation facilities	En	PSA
Évora Atmospheric Sciences Observatory	RS + IS	UÉ
Biochem lab and cell culture lab	Lab	UÉ
Solar Radiation Monitoring stations of Évora and Beja	RS	UÉ
Laboratory for controlled cell exposure to aerosol at air–liquid interface	Lab	ZAUM
Cyprus Atmospheric Remote Sensing Observatory	RS	ECoE
Earth Surface Mineral Dust Source Investigation (EMIT) mission	Satellite RS	NASA
Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) mission [3]	Satellite RS	ESA/JAXA

Seventeen Ph.D. projects have been proposed to advance the corresponding scientific questions (Table 2). With this network, we aim to provide significant scientific advances in the four research objectives outlined in the table:

- RO1 is about understanding the fundamentals of dust microphysical properties and processes, and, in particular, we aim to tackle the impact of non-spherical particles, which are not always considered due their complexity; moreover, we will investigate the effect of turbulence on atmospheric residence times and the impact of ice nucleation on dust.
- RO2 will focus on the influence of source regions on dust properties, overcoming some simplifications that see dust as a homogeneous aerosol type, combining experimental approaches (source-dependent composition, microphysical properties and spectral signatures) with modelling efforts (climate–mineralogy relationships).
- RO3 will tackle some of the socio-economic aspects, and, in particular, we aim to advance knowledge on impacts on health, air quality planning, aviation and solar energy production.
- RO4 will address the role of dust in the climate system, aiming to exploit novel space-borne observations and modelling tools together with gaining a better understanding of processes (radiative effects and transport mechanisms).

Table 2. Dust-DN research objectives and Ph.D. projects.

Research Objectives	Ph.D. Projects	
RO1: Understanding the fundamentals of dust microphysical properties and processes	DC2	Dust particle shape, aspect ratio and orientation: new information from UAV campaigns
	DC4	Atmospheric Sedimentation of Non-Spherical Dust Particles: Developing knowledge for improvement of models
	DC10	New scattering database for desert dust, with realistic size, shape and refractive index measured in-situ
	DC14	Size-dependent turbulent dust transport in idealised and realistic high-resolution simulations
	DC17	Ice nucleating dust particle concentration profiling and effects on ice crystal formation
RO2: Identifying the influence of source regions on atmospheric dust properties	DC12	Modelling the effects of dust upon regional climate with constrained dust-source mineralogy
	DC13	Variability of dust composition, shape and size distribution across the Mediterranean, based on single-particle analysis
	DC15	Identification of dust properties from different sources using sun-photometry and their effects on spectral solar irradiance
	DC16	Quantification and characterisation of dust microphysical properties in the Mediterranean and Middle East, through the novel Aerotape technology
RO3: Socio-economic impacts of dust on health, aviation and energy production	DC1	Modelling impacts of aeolian dust towards air quality policy planning
	DC5	The impact of mineral dust on Aircraft Engines in the Middle East
	DC6	Modelling and assessment of the impact of atmospheric dust on solar resource for energy applications
	DC8	Assessment of the respiratory health impact of atmospheric dust
RO4: Dust in the global climate system	DC3	Global dust estimation from novel space missions
	DC7	Enhancing the understanding of dust direct radiative effect
	DC9	Modelling of dust transport processes. Bridging the gap between theory, observations, and models
	DC11	Modelling super-coarse dust and its effect upon climate

3. First Results

The first experiments and first modelling simulations for the anticipated advances in dust science have started and are outlined here.

In April–May 2025, the Cyprus Spring Campaign 2025 was carried out to advance measurement techniques for dust sample collection and to investigate the composition, size, shape and orientation of atmospheric dust particles. A mix of ground-based remote sensing and airborne in situ and ground-based instrumentation was used, including the collection of high-altitude dust samples. Some major dust events were captured (see example in Figure 1) and the analysis of the datasets collected is ongoing.

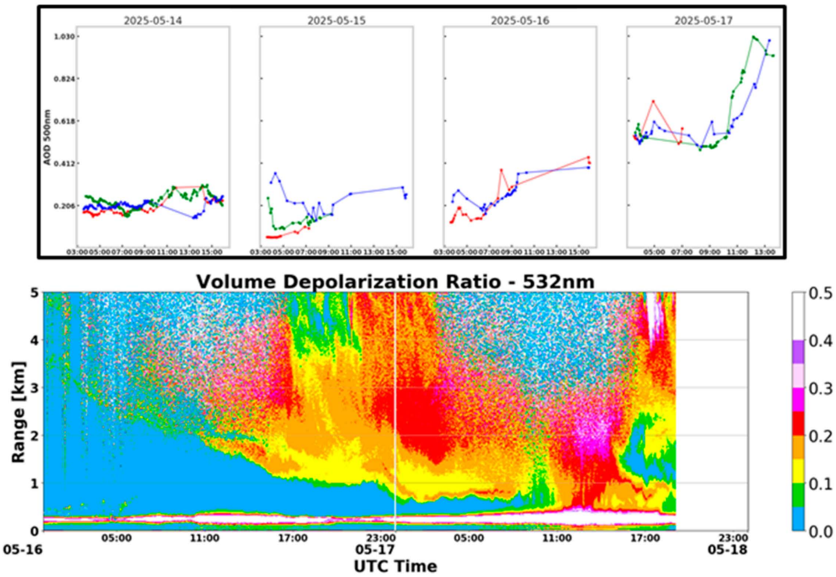

Figure 1. Aerosol optical depth (AOD) in Cyprus on 14–17 May 2025, and volume depolarization ratio observed during 16–17 May. The large AOD (increasing up to 1) and large depolarization ratio (up to 0.3) clearly identify the dust event. High-altitude dust samples taken in these atmospheric conditions will be analysed using scanning electron microscopy. Blue line: Nicosia; Red line: Agia Marina Xyliatou; Green line: Limassol.

During this campaign, moreover, observations using AEROTAPE (Oberon Sciences, Grenoble (Villard-Bonnot), France), a novel cost-effective scientific instrument, sampled the atmospheric dust on the ground at high resolution, providing novel imagery of the dust particles that is very useful for their quantification (see examples in Figure 2).

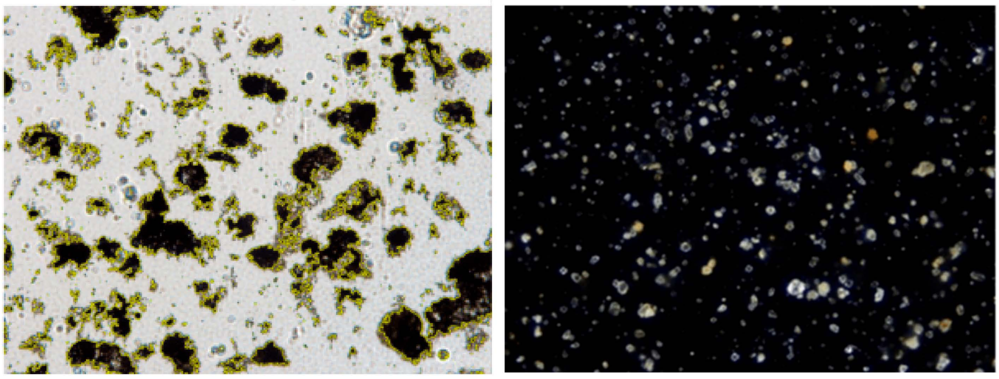

Figure 2. Images of dust particles collected by AEROTAPE during the Cyprus Spring Campaign 2025. AEROTAPE uses an onboard camera to capture images every ten minutes, and is able to analyse them automatically to provide their count, size, shape and colour.

At the same time that these experiments were carried out in Cyprus, simulations started at the Barcelona Supercomputing Centre using the Multiscale Online Nonhydrostatic AtmospheRe Chemistry (MONARCH) model, with the aim to integrate them with high-resolution satellite observations from the NASA EMIT mission, providing information about surface mineralogy at the major dust source regions (see example in Figure 3).

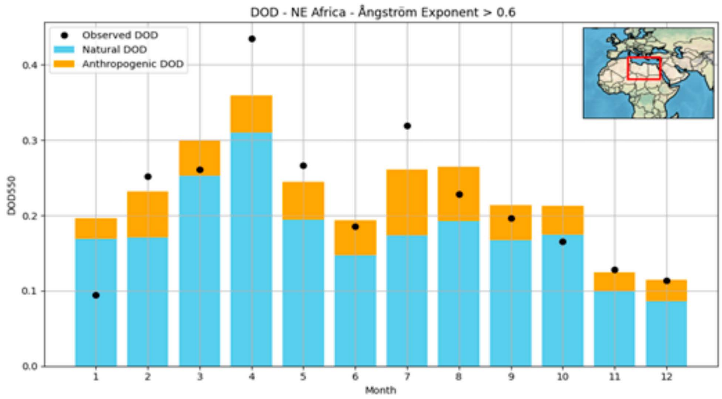

Figure 3. Comparison between the dust optical depth (DOD) over Northeast Africa simulated using MONARCH and the observations available from AERONET.

4. Conclusions

The strength of addressing research objectives with a doctoral network, as opposed to individual specialised projects, resides in the international, interdisciplinary and intersectoral approach, which valorises each methodology and the specialisations of each partner to address the topic of atmospheric dust from several points of view. This will be reinforced through advanced training and networking opportunities for the doctoral candidates. Each of them will be supported through an individualised career development plan and a number of secondments to be carried out during the project, and all of them will be gathered together for network-wide schooling and workshops. They will also be encouraged to build team spirit through more frequent virtual networking opportunities.

Dust-DN is more than a collection of 17 visionary Ph.D. projects on mineral dust; it will create a dust science community that will enhance the potential of a number of unique techniques and facilities. It is expected that the network will advance the science of atmospheric dust, will further develop scientific synergies and complementarities, and will train a cohort of dust experts of tomorrow.

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Abbreviations

The following abbreviations are used in this manuscript:

Dust-DN	Dust Doctoral Network
DC	Doctoral Candidate

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