University of Pécs

Doctoral School of Earth Sciences

Summary Booklet of the PhD dissertation

THE IMPACT OF EOLIAN DUST PARTICLES AND DUST STORMS ON CLIMATE CHANGE

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1 Introduction

Researchers investigated the impact of natural and anthropogenic aerosol perturbations on the climate system using tropospheric physicochemical parameters (Wallace and Hobbs, 2006; Patúc, 2021). Thus, the troposphere is the first atmospheric layer visible from ground level and the atmospheric layer where most meteorological phenomena occur. Human actions have a significant impact because it is so close to the Earth's surface.

Furthermore, aerosols can disrupt several climate-regulating processes (Allen et al., 2016; Hagen & Azevedo, 2024; Miinalainen et al., 2022). For instance, they can directly impact by diffusing and absorbing solar and telluric electromagnetic radiation, impacting the energy exchange in the atmosphere and the Earth's surface. Because radiative energy is the driving force behind the atmospheric thermal system, aerosol suspension directly affects all atmospheric energy transfer processes. As a result, the atmosphere reacts differently depending on the presence of aerosols. The direct effect influences cloud development and/or maintenance in response to thermodynamic atmospheric changes (semidirect effect). Aerosols can, therefore, impact cloud formation and cycling through cloud microphysics (indirect effect) (Li et al., 2021; Nabat et al., 2022).

Over the past several decades, the North African deserts have been identified as the primary source of mineral dust around the world (Engelstaedter et al., 2006; Francis et al., 2020; Goudie & Middleton, 2001; Purr et al., 2021; Varga, 2020). Dust emissions and transport exhibit high variability between daily and decadal time scales (Di Biagio et al., 2021). The different impacts of the desert dust have been more detailed in the thesis manuscript.

Because of its impact on central Europe, dust deposition has become a key topic under investigation (Panait et al., 2019; Rostási et al., 2022; Szuszkiewicz et al., 2023; Varga, 2020). According to previous studies, the deposit of dust plumes from the African desert significantly altered a separate physical atmospheric process in the climate system, altering precipitation properties. Dust accumulations may result in vision issues, stains on cars and windows, red skies that lead to rain, etc.

In this regard, our research focused on the dust released by North African deserts (Ginoux et al., 2012; Mahowald et al., 2014; Wang et al., 2018; Engelstaedter et al., 2006; Francis et al., 2020; Goudie and Middleton, 2001; Purr et al., 2021; Varga, 2020). This natural source of aerosol study is an intriguing question for various reasons, including its impact on human health, climate, and environmental issues (Anderson et al., 2012; Regina et al., 2011). Indeed, discussing the projected frequency, and spatiotemporal distribution of desert dust and the processes that create it are essential to discuss its implications.

Problem statement

As previously noted, aerosols significantly impact radiative balance and air quality (Anderson et al., 2012; Akimoto, 2003; Allen et al., 2016). Studying aerosol optical and radiative properties has become a significant topic in scientific research on future climate and general environmental and health-related issues. Despite considerable scientific advancement throughout all domains, questions about the role of aerosols in atmospheric and terrestrial radiation balance remained (Di Biagio et al., 2021; Carslaw, 2022).

Once aerosols are released into the atmosphere, they undergo various processes that determine their evolution. Aerosols can change size and/or chemical composition as a result of weathering process. This evolution occurs through multiple mechanisms, such as the condensation or evaporation of gaseous species on particle surfaces, chemical interactions, particle coagulation, and even the activation of cloud condensation nuclei that produce cloud drop or ice particles. All aerosols, once suspended, can be returned to the surface by dry and wet deposition processes.

The ambiguity surrounding calculating aerosol optical properties originates mainly from difficulties in understanding the physicochemical behavior of these particles from emissions to a deposition process. Reducing aerosol uncertainties requires enhancing the quality of observation data ensembles and combining them with atmospheric models. Atmospheric models, combined with measurement campaigns, have become critical instruments for evaluating the impact of aerosols on air pollution and radiative balance. The inclusion of aerosols into numerical models remains a challenging task. Indeed, processes impacting aerosols occur on spatial and temporal scales that are not always easy to model.

This raised two scientific concerns that define the two main lines of interest to obtain the current study: first, estimating the spatiotemporal distribution of desert aerosols by tracking desert dust events from emission to deposition area. Second, assess the meteorological impact of this disturbance on the trajectory of the desert aerosol plume, and third, identify the qualitative and quantitative physicochemical features of these aerosols.

2 Research Objectives

Given these challenges, the current work aims to be at the intersection of the following axes: Firstly, we focused on defining sediment deserts using experimental and analytical methods to assess the physical-chemical composition of an ensemble of surface samples collected from Tunisian desert areas.

Secondly, the current work intends to examine the spatiotemporal variation of Saharan dust episodes utilizing combined approaches, which include the following methods:

(1) comprehend the paths taken by tracking the Saharan dust Events from the Tunisia desert to Central Europe using the forward trajectories HYSPLIT model simulations from 2005 to 2021;

(2) We investigate the spatiotemporal variations of the desert dust emission and Deposition by using the monthly seasonal trending of the AOD550 MODIS data and MERRRA-2 dry and wet deposition over the study period.

(3) We investigated the synoptic weather patterns of the Saharan dust events over the same study period.

(4) The validation of the synoptic analysis outcomes of the Saharan dust events by the daily monitoring of the Saharan dust load using the METEOSAT dataset.

Thirdly, we investigated the relationship between the temporal change of climatic parameters (clouds, temperature, precipitation, etc.) and the occurrence frequency of Saharan dust.

3 Description of the study area:

Tunisia, the northernmost country in North Africa, borders Algeria, Libya, and Italy. It features mountain landscapes and the Sahara desert, which covers about 40% of its area. The desert includes salt flats, vast plains, and towering sand dunes.

We selected Tozeur, Kebili, Tataouine, Gabes, and Medenine to study dust plume trajectories. Tunisia’s atmospheric circulation, influenced by various air masses, governs dust movement. Notable air masses include maritime polar from Eastern Europe and Siberia, continental tropical from the North Atlantic, and dry continental from the Sahara and Azores . El Melki (1991, 1996; El Melki, 1996). Several geographical factors influence tropical and subtropical weather, including proximity to the Atlantic Ocean, Mediterranean Sea, and deserts like the Sahara and Sahel.

Our study focuses on African Saharan Desert events occurence in central Europe, particularly Hungary’s geology, geography, and climatology. Central Europe includes the Danube areas like Croatia, the Czech Republic, Hungary, Poland, Romania, Serbia, Slovakia, Slovenia, and often Germany. The region experiences cold, dry winters and hot, humid summers.

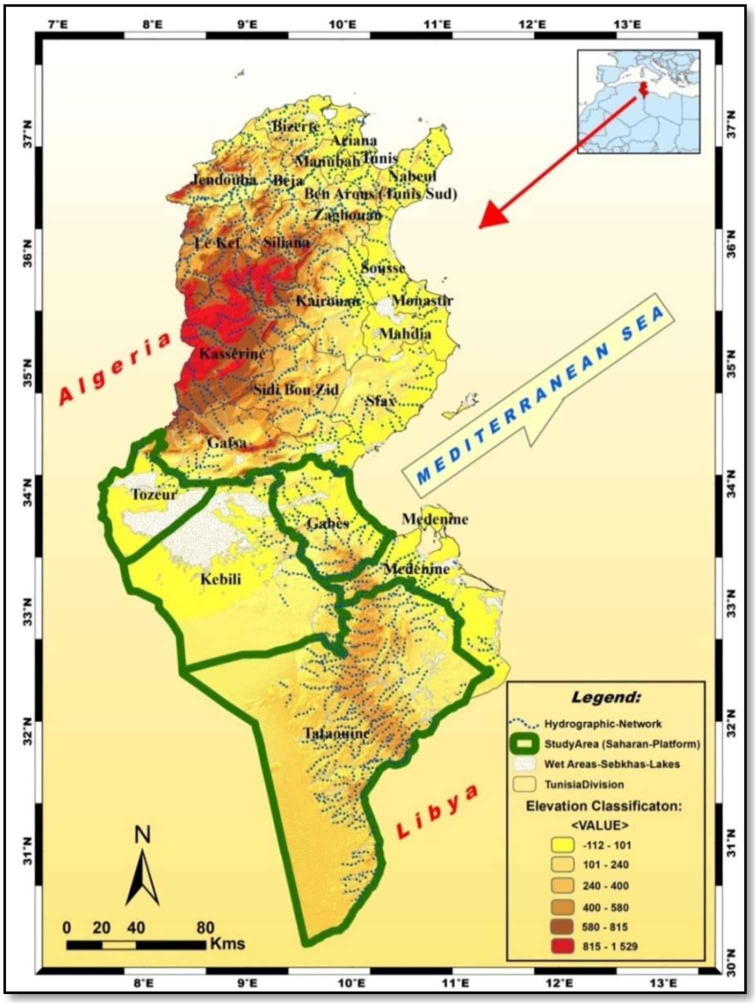

Figure 1.1: Location of the case study area.

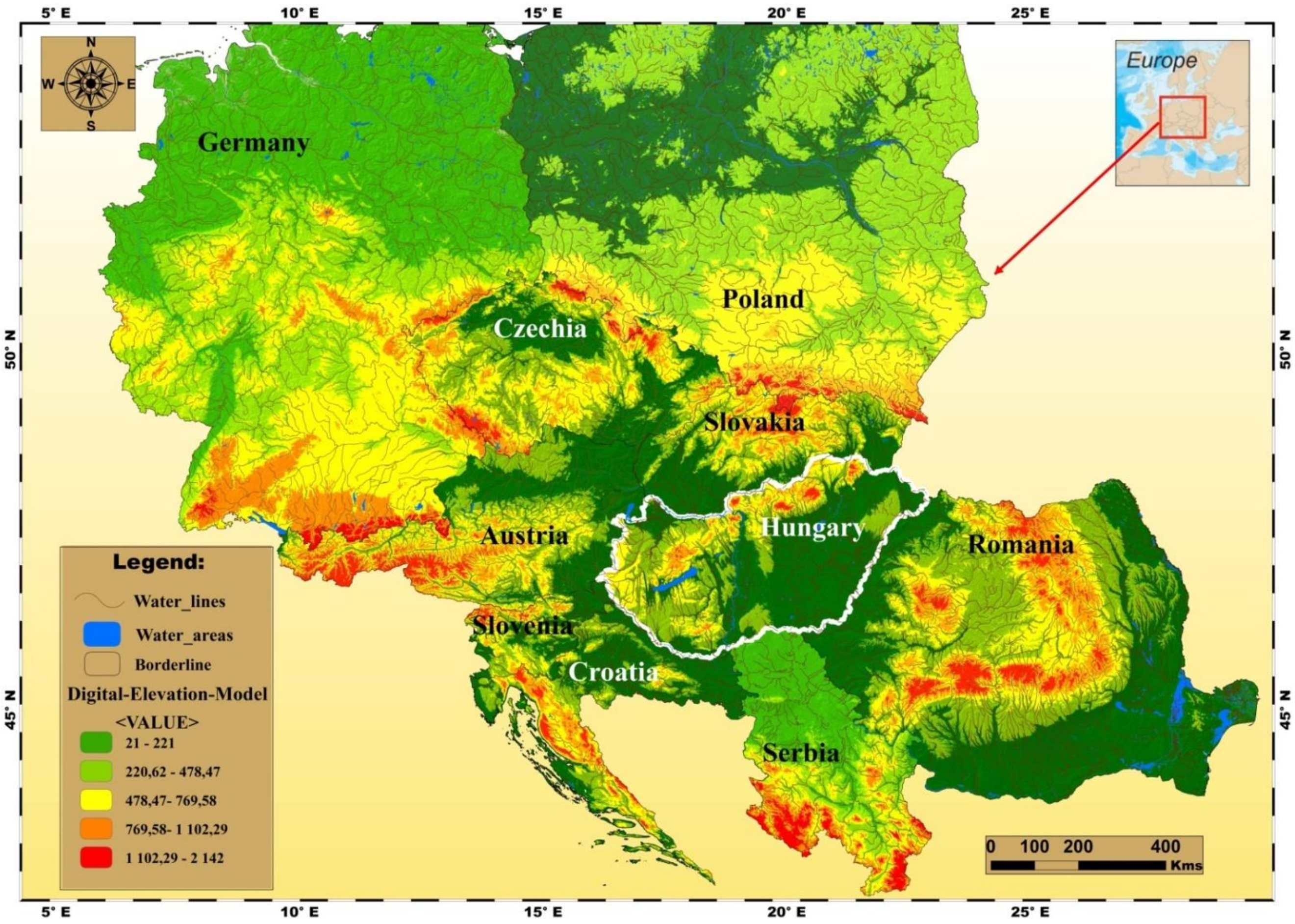

Figure 2.1: Hungary's geographical location inside Central Europe.

4 Research methods:

The methodology of this research is divided into two main parts. First, we calculated HYSPLIT air mass trajectories, daily AOD, and MERRA-2 observations, along with dust plume concentrations, to identify potential source areas for SDEs. We then assessed the synoptic conditions of these SDEs using weather maps. Below is a detailed description of each approach:

4.1 Hysplit model simulations:

4.2 Spatial-temporal Distribution of AOD and MERRA-2 dataset:

4.3 Synoptic analysis:

4.4 The XRD analysis

XRD was used to gain a mineralogical understanding of the sedimentary material in the source areas. Accordingly, several sites were sampled in the Tunisian regions.

4.5 Scanning Electron Microscopy (SEM):

We used scanning electron microscopy to investigate the minerals in our samples. This examination identified different mineral components in the samples based on their shape and quality.

The EDS analysis gathered the X-rays emitted by the electron beam and sample contact, displaying a spectrum of the elements' respective intensities. Thus, the EDS mode determines the mineral's elemental composition.

4.6 The grain size distribution:

5 Scientific Results:

Result 1:

From 2005 to 2021, we tracked Saharan dust from the Tunisian desert using the HYSPLIT model and counted Saharan Dust Events (SDE) in Central Europe. Our model shows that dust pathways vary with SDE intensity and time scale. Monthly analysis indicates spring and summer peaks are linked to shifts in thermal convective instability. Thermal convective instability can inject particles to higher altitudes. Unseasonable SDEs, occurring mainly from October to February, have different causes, which are explained in the following paragraphs.

Using the Aerosol optical parameter, this approach investigated the seasonal change of air parcels in these locations. Based on the obtained results, the method can be applied as a supporting technique for the spatiotemporal distribution of the desert Aerosol Depth over the study period. It is employed to verify the relationship between seasonal trends and SDE frequency. The findings demonstrate monthly variations in the AOD average for Algeria, Libya, and Tunisia. This measure yields dependable outcomes when describing the spatial-temporal distribution of air aerosols across various regions with a dry climate and certain limitations. For instance, only locations free of snow and clouds may achieve its implausible quantization of the low AOD range (AOD < 0.1) (Gui et al., 2021). Further, overwhelming dust plumes moved across low latitudes cannot be recovered using the AOD approach (Kahn et al., 2005; Witek et al., 2013).

This model aids aerosol studies in central Europe, where in-situ observations are rare and cloud cover complicates aerosol observation. Despite reliable analyses, MERRA2 has drawbacks, such as overestimating fine-mode aerosols and underestimating high AOD. It also struggles with orographic structures, making mountain dust estimations challenging.

Result 2:

We validated the HYSPLIT model using AOD data to describe desert dust occurrences. AOD values peaked in spring (≥ 0.30) and summer (≥ 0.20) in Tunisia's desert, with lower values in autumn (≤ 0.30) and winter (≤ 0.20). Higher AOD in spring and summer is linked to Saharan dust, while low values are due to geological factors, low population density, and minimal human activity

Secondly, MERRA-2 variability shows a change in dust deposition across a 10- to 11-year timescale, indicating a change in natural occurrence over time. This idea refers to prior studies (Lockwood, 2012; Mursula & Zieger, 2000; Lorenzen, 2019), which proposed a mechanism for an indirect effect of solar forcing on climate via solar electromagnetic radiation. This solar radiation cycle lasts 10 to 11 years and includes phases of high and low activity. During times of high solar activity, wind-solar production must be responsible for climate change on Earth. Temperature is a significant climatic variable. Therefore, increased solar activity significantly impacts the regional climate in Central Europe.

Result 3:

We investigated dust storms using atmospheric weather variables and meteorological maps from NCEP/NCAR. The synoptic analysis revealed seasonal patterns of desert dust activity. In spring, gradient pressure creates a frontal system that drives wind direction and speed, causing dust storms. The study also confirmed microscale cyclogenesis over the Atlas Mountains, transporting dust to the Mediterranean.

Moreover, the synoptic analysis revealed that the current dust occurrences of the Saharan dust events are more frequent and intense than those of earlier dust events. These unusual patterns are likely connected to the function of the jet stream. This intensive appearance of winter SDE arguments by the influence of Arctic amplification in changing system circulation patterns referring to the change in surface air temperature over the Arctic (Varga, 2020, Gammoudi et al., 2024).

Result 4:

Our study found that meteorological conditions affect dust storm frequency. We observed that wind speed and temperature variations correlate with Saharan dust outbreaks. In Central Europe, wind influences the arrival of Saharan dust, while cloud and precipitation affect dust deposition.

In spring, daily changes in temperature and precipitation affect soil properties, making it easier for wind to uplift dust. Wind speed plays a key role in dust storm formation, especially without precipitation. Increased temperature and decreased precipitation, influenced by global climate factors like NAO, ENSO, and MO, lead to more frequent dust storms. Arid climates are ideal for transporting windblown dust over long distances.

Result 5:

We used second-generation Meteosat satellites to track desert dust events and validate our synoptic analysis. Long-term monitoring with Meteosat data has proven reliable, especially when combined with tracking aerosol optical thickness. Meteosat observations confirm high aerosol optical thickness in emission and deposition zones due to desert dust.

Desert dust has seasonal distributions, forming dust clouds in late spring and summer. Strong winds can carry Saharan dust across the Mediterranean to Europe. Meteosat satellite data confirmed that desert dust combines with anthropogenic and marine dust in central Europe. Identifying and characterizing mineral dust using in-situ measurements helps pinpoint aerosol sources.

Result 6:

Our analysis of desert samples revealed intricate compositions similar to North African dust. In Tunisian deserts, we found various evaporates and clay minerals distinguishing arid from semiarid environments. Samples from Tataouine had unique compositions, including different sodium sulfates.

Grain size distribution analysis classified samples into low, moderate, and high-bimodality structures. Results showed unimodal, bimodal, and trimodal distributions. Unimodal curves had the highest coarse grain size, while bimodal curves showed two peaks. Bimodal distribution was the main pattern, highlighting medium and coarse fractions.

The grain size distribution shows that medium and coarse grains dominate our samples, allowing us to identify clay minerals, which are mostly absent in desert samples. Clay minerals are found in Chott Elgharsa, Chott Jerid, Tatouine's Sebkha, and Matmata plateau samples. Scanning electron morphostructure reveals that the samples mainly contain calcium carbonates, quartz, sodium sulfates, and clay particles. The samples include a variety of minerals such as calcite, dolomite, gypsum, anhydrite, halite, clays, quartz, feldspars, and goethite. Calcite, dolomite, and salt minerals like calcium sulfate and sodium chloride are key indicators of dry lakes in Tunisian terrains.

XRD measurements detected detrital minerals (clay minerals, quartz, feldspars), carbonate minerals (dolomite, calcite), and evaporitic minerals (halite, thenardite, mirabilite). Clay minerals include sepiolite and palygorskite. Samples from Sebkhet Elkhialat revealed mirabilite and thenardite, indicating a cold-dry climate. Despite previous findings, our samples showed rare clay minerals, likely due to the identification method used. SEM and EDS results revealed sepiolite mainly associated with palygorskite. Sepiolite, a hydrated magnesium silicate, has various economic applications in industrial, health, and biotechnology domains.

6 Conclusions:

To accomplish the objectives of this research, we used two different scientific methodologies.

Firstly, we used standard measurement approaches to determine the mineralogical compositions of samples collected from various desert environments in Tunisia. These measurements, including the SEM and the XRD, in which we identified the morphology and the composition of desert sediments and the grain size distribution analysis using the wet laser diffraction equipment.

In this regard, the analyses' findings confirmed the compositions of the typical North African desert, including calcium carbonate such as calcite dolomite and the presence of quartz, gypsum, and halite. However, the mineralogical composition revealed unusual results of some samples taken from the deserts of Tunisia. For example, the samples collected at Tatouin'Sebkha showed a different composition from those from other sampling terrains, including the distinctive Sodium Sulfates (thenardite, mirabilite, etc.). Furthermore, our findings showed that a particular clay mineral, such as sepiolite combined with other minerals, is present and that this mineral facilitates the distinction between semiarid and dry environments.

Because identifying some mineral compositions is difficult, we emphasize the importance of improving qualitative studies through elemental composition analysis, such as XRF analysis.

Secondly, we used a combined approach, such as the Hysplit atmospheric model and the AOD observation and model dataset, to estimate the spatiotemporal distribution of the SDE emitted from North Africa, the METEOSAT meteorological images, and weather maps. For this purpose, we tracked the dust from the African desert to the reception location using the HYSPLIT model. Besides, we compared the AOD concentration results with those of the Hysplit model.

We next looked into the synoptic analyses and the metosat dataset images to identify the different atmospheric variables influencing the SDE's life cycle. These findings showed a seasonal cycle fluctuation in desert dust over the year. Furthermore, the correlation between dust dispersion and seasonal variations draws our attention to the possible influence of meteorological factors on dust dominance. The synoptic investigation validated the seasonal and inter-annual fluctuation of the SDEs. The synoptic analysis also highlights the importance of Arctic amplification in the dominance of the polar jet stream, which is primarily responsible for the SDE's arrival into Central Europe.

The thesis also highlighted several probable causes of cyclone development over the source region, which may be partially responsible for the dust dispersal across Central Europe. The summary of this discussion leads us to conclude that there is a fundamental link between the occurrence and severity of SDEs and the cyclical variation of the global dynamic climate. This correlation may help to explain SDE transport at higher altitudes and on a shorter time scale.
For example, increasing surface heating in the source location leads Saharan dust to rise into the higher air level, allowing for faster and longer-distance transmission. The HYSPLIT model's results show it is remarkably accurate at identifying potential desert dust paths. Similarly, we can use AOD parameters to determine the overall distribution of total aerosols in the atmosphere. We also briefly reviewed the variability of SDEs at the interannual and daily scales.

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List of own publications on the topic

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Gammoudi, N., Kovács, J., Gresina, F. & Varga, G. (2024) Combined use of Hysplit model and MODIS Aerosols Optical Depth to study the spatiotemporal circulation patterns of Saharan dust events over Central Europe. ***Aeolian Research*** 67-69, 100899. doi: 10.1016/j.aeolia.2024.100899 – Q1
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