DOI: 10.15201/hungeobull.72.4.1 Hungarian Geographical Bulletin **72** 2023 (4) 319–337.

Increasing frequency and changing nature of Saharan dust storm events in the Carpathian Basin (2019–2023) – the new normal?

György VARGA[1,2,3], Ágnes ROSTÁSI[2,4], Aida MEIRAMOVA[2,4], Pavla DAGSSON-WALDHAUSEROVÁ[5,6] and Fruzsina GRESINA[1,3]

Abstract

The number and intensity of Saharan dust storm events identified in Europe has been increasing over the last decade. This can be explained by the role of ongoing climate change. An extension of previous studies covering a 40-year period is presented in this paper, with new data on the frequency, synoptic meteorological background, source areas, grain size, grain shape and general mineralogy of deposited dust for the period 2019–2023 in the Carpathian Basin. A total of 55 dust storm episodes have been identified in the region over the five-year period, which is significantly higher than the long-term average. The classification based on synoptic meteorological background clearly showed that the frequency of circulation types with a more pronounced meridional component increased and dust material reached further north more frequently than before. In several cases, large amounts of dust were deposited, from which samples were collected and subjected to detailed granulometric analysis. The varied grain size data showed that coarse silt (20–62.5 μm) and sand (62.5 < μm) fractions were also present in large quantities in the transported dust material.

Keywords: Saharan dust, climate change, Carpathian Basin, grain size

Received October 2023, accepted December 2023.

Introduction

The changing climate has increased the importance of atmospheric research in recent decades. The combined study of the many interconnected components of the Earth system is necessary to gain a deeper understanding of the scale and rate of change in the atmosphere, and to unravel the interconnections between them, on a scale and at a rate not previously known in human history (Easterling, D.R. *et al.* 2000; Shepherd, T.G. 2014; IPCC, 2022). A key part of this is the study of atmospheric components traveling with the major circulations and the winds driven by these airflow systems over long distances (Harrison, S.P. *et al.* 2001; Kohfeld, K.E. and Tegen, I. 2007; Maher, B.A. *et al.* 2010; Pósfai, M. and Buseck, P.R. 2010).

Over the past decades, atmospheric mineral dust has been in the focus of climate and environmental research. The emission, transport and deposition of particulate matter has an impact on our environment

[1] Geographical Institute, HUN-REN Research Centre for Astronomy and Earth Sciences, Budaörsi út 45. H-1112 Budapest, Hungary. Corresponding author's e-mail: varga.gyorgy@csfk.org

[2] Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary.

[3] ELTE Department of Meteorology, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, Budapest, Hungary.

[4] Air Chemistry Research Group, Research Institute of Biomolecular and Chemical Engineering, University of Pannonia, Veszprém, Hungary.

[5] Faculty of Environmental and Forest Sciences, Agricultural University of Iceland, Reykjavik, Iceland.

[6] Department of Water Resources and Environmental Modelling, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic.

locally, regionally and globally (Monteiro, A. *et al.* 2022). Mineral particles with a wide variety of material properties are released into the atmosphere and scatter, reflect and absorb radiation from the sun, directly modifying the irradiance patterns (Arimoto, R. 2001). The role of particulate matter in cloud formation is considered as an indirect radiative effect (Nickovic, S. *et al.* 2016; Rieger, D. *et al.* 2017; Weger, M. *et al.* 2018; Adebiyi, A.A. *et al.* 2023). For a given water vapour content, the increased atmospheric particle number also increases the number of condensation nuclei required for cloud and ice formation, thus contributing to the formation of more but smaller cloud elements (Hoose, C. *et al.* 2008; Nickovic, S. *et al.* 2016; Ginoux, P. 2017; Kok, J.F. *et al.* 2017; Ansmann, A. *et al.* 2019). This will result in the formation of lighter but longer-lived clouds due to the dust-loaded air masses. Other environmental effects of long-range mineral particles at the point of deposition are also significant: in soil formation (see e.g., Terra rossa soils of the Mediterranean – MacLeod, D.A. [1980]; Jackson, M.L. *et al.* [1982]; Jahn, R. *et al.* [1991]; Atalay, I. [1997]; Muhs, D.R. *et al.* [2010]); in the carbon cycle through the iron and phosphorus supply to ocean and marine ecosystems (Ridgwell, A.J. 2002); in the modification of precipitation pH (Rodá, F. *et al.* 1993; Rogora, M. *et al.* 2004; Čanić, K.Š. *et al.* 2009) and in many other processes (for details, see e.g., Meinander, O. *et al.* 2022; Monteiro, A. *et al.* 2022).

Every year, billions of tons of mineral dust are picked up by the winds from arid semi-arid regions and transported, sometimes thousands of kilometres (Tegen, I. and Lacis, A.A. 1996; Mahowald, N.M. *et al.* 1999, 2006; Ginoux, P. *et al.* 2001). The main source areas are in the Sahara, from where the dust is transported to the Atlantic (as far as the Americas); northwards to Europe; and eastwards to the Middle East.

The frequency of dust transport to Europe has changed in recent years (Varga, Gy. 2020; Hrabcak, P. 2022; Salvador, P. *et al.* 2022; Cuevas-Agulló, E. *et al.* 2023; Kok, J.F. *et al.* 2023). In Spain, France, Central Europe, the Carpathian Basin and even at higher latitudes such as Greenland (Francis, D. *et al.* 2018), Iceland (Varga, Gy. *et al.* 2021), and Finland (Varga, Gy. *et al.* 2023), the changing flow patterns and the occurrence of African dust have been noticed. The general picture of the Saharan dust masses and dust storm events reaching the Carpathian Basin over the last 40 years has been described in great detail in previous publications (Varga, Gy. *et al.* 2013; Varga, Gy. 2020). In this paper, we present the frequency and intensity variations observed in the last few years, including the characteristics of the grain size and particle size distribution of the transported dust.

Material and methods

Study area

We investigate Saharan dust events reaching the Carpathian Basin (45°–48.5° N, 16°–23° E). This closed basin in central Europe is bounded by the Alps, Carpathians and Dinarides mountain ranges. The climate and weather are determined by three meteorological regimes: Atlantic, Continental and Mediterranean. Previous research by Varga, Gy. (2020) on dust storm events from the Sahara has shown that air masses of African origin typically transport desert dust into the region in spring and summer. Winter dust storm events have also increased in the last decade, sometimes accompanied by significant deposition and muddy rain. From 1979 to 2018, 218 Saharan dust storm events have reached the Carpathian Basin, with a clear increasing trend in the time series.

Identification of dust storm events

For reasons of consistency with previous research, the same methodology was used as before. Potential dust storm events were identified using standardised values from daily TOMS, EP and OMI Aerosol Index data available since 1979. Verification of the potential events was based on a multi-step procedure using satellite imagery, modelling of the air trajectory propagation by HYSPLIT back-trajectory (HYbrid Single-Particle Lagrangian Integrated Trajectory – Stein, A.F. *et al.* 2015), CALIPSO aerosol v4.10 subtype vertical profiles (https://www-calipso.larc.nasa.gov/) to verify the presence of mineral dust in the air column, and the MERRA-2 Dust Column Mass Density dataset available since 1980 (Area-Averaged of Dust Column Mass Density [M2T1NXAER v5.12.4] – Gelaro, R. *et al.* [2017] – data were obtained from Giovanni application for visualisation and access Earth science remote sensing data platform [https://giovanni.gsfc.nasa.gov/giovanni/]). Also from the MERRA-2 database are the wet and dry dust deposition data (Dust Dry Deposition Bin-all: M2TMNXADG v5.12.4; Dust Wet Deposition Bin-all: M2TMNXADG v5.12.4; Dust Dry+Wet Deposition Bin-all: M2TMNXADG v5.12.4).

In addition to the areal averages of the MERRA-2 datasets, we also used spatial flux data of dust dispersion and the Barcelona Supercomputing Center NMMB/BSC model (Pérez, C. *et al.* 2011; Klose, M. *et al.* 2021), where dust load, dry and wet deposition values were estimated using the SDS-WAS (Sand and Dust Storm Warning Advisory and Assessment System) interface.

Synoptic meteorology

Synoptic meteorology-based typing of individual events was based on the Daily Mean Composite application of NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/) using the NCEP/NCAR (National Centers for Environmental Protection / National Center for Atmospheric Research) Reanalysis Project dataset (Kalnay, E. *et al.* 1996) 700 hPa potential level, meridional and zonal wind components, and wind vectors. The use of the 700 hPa level as a vertical level, also considered as a typical transport altitude, has been shown to be characteristic in previous studies (Alpert, P. *et al.* 2004; Barkan, J. *et al.* 2005; Varga, Gy. *et al.* 2013). To analyse the possible role of high-altitude eddy-driven polar jet stream flow and its changing patterns, data for the 250 hPa level were also examined.

Granulometric analyses

Mineral dust samples collected during dust storm events coinciding with intense deposition were analysed using automated static image processing technology with a Malvern Morphologi G3-IDSE. During the study, the size and shape parameters of tens of thousands (typically 50,000) of individual grains are automatically recorded during scanning with a 40 pixel per μm^2 resolution objective.

Among the available parameters, we used the circle-equivalent diameter, high-sensitivity circularity, convexity, aspect ratio, solidity and grayscale intensity determined as a function of transmittance. Circle-equivalent diameter is calculated as the diameter of a circle with the same area as the projected two-dimensional particle image.

The shape parameters are highly dependent on the size of the grain (partly for measurement-technical reasons), so the 5–40 μm range was investigated for shape-analyses. An accurate indicator of the circularity property is the high sensitivity (HS) circularity, which is calculated by the instrument as the ratio of the projected area of the grain to the square of its circumference. Solidity value is given by the ratio of the area of the investigated object to the area enclosed by the convex hull, while aspect ratio is the ratio of the width to the length of a given particle. The value of convexity is determined by dividing the circumference of the convex hull by the circumference of the grain. The perimeter of the convex hull is the smallest convex polygon containing the area of the grain.

In addition to automated image processing, mineral composition studies were also performed using a Raman spectrom-

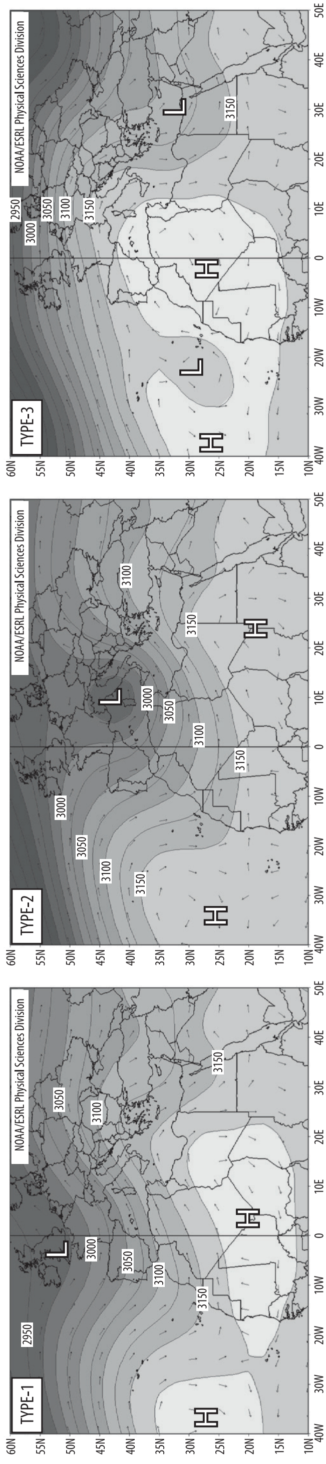

Fig. 1. Synoptic meteorological background (mean geopotential height map and wind vectors at 700 hPa) of different types of Saharan dust events. *Source:* Varga, Gy. 2020.

eter (Kaiser Optical Systems Raman Rxn1 Spectrometer, 785 nm, < 500 mW) as part of the instrument, after correlating the recorded spectra of selected grains with a reference database (BioRad-KnowItAll Informatics System 2017, Raman ID Expert).

Results

Saharan dust storm events in the Carpathian Basin

The identified dust storm events were classified into three main groups based on their synoptic meteorological background and closely related air mass trajectories. A detailed description of the classification can be found in Varga, Gy. (2020). The most frequent events (about two thirds of all events) are associated with the southward flow of the high-altitude atmospheric trough over the Eastern Atlantic basin, and mainly Saharan dust storm events transported over the Western Mediterranean basin are placed in this cluster. African air masses arriving into the Carpathian Basin over the Central Mediterranean basin with the frontal flow of the Mediterranean cyclones were classified as Type-2, accounting for a quarter of all episodes. The relatively rare Type-3 events, under which conditions dust material was drifting over the Atlantic Ocean and then became long-range dust transport episodes with westerly winds, accounted for 8 percent of all events over the last four and a half decades *(Figure 1).*

The previously published database has been extended to November 2023, and now contains 273 identified Saharan dust storm events from 1979 onwards. The time series and seasonality distributions, completed with MERRA-2 deposition data, are shown in *Figure 2* and *Table 1*. The data clearly demonstrate that the number of dust storm events in the region has increased over the last decade and a half. During the first three decades of the period under study, an average of 3–5 episodes per year hit the Carpathian Basin. This number increased to

Table 1. Decadal, seasonal and type-specific frequencies of Saharan dust storm events in the Carpathian Basin between 1979 and 2023

Types and seasons			Decades					
			1998–2008	1989–1998	1999–2008	2009–2018	2019–2023*	*Total*
Type-1	Seasons	spring	14	10	15	17	10	*66*
		summer	14	4	15	24	10	*67*
		autumn	2	2	3	9	10	*26*
		winter	2	–	2	13	5	*22*
	T1 total		32	16	35	63	35	*181*
Type-2	Seasons	spring	7	6	8	7	6	*34*
		summer	–	–	2	2	2	*6*
		autumn	3	1	2	4	1	*11*
		winter	4	–	2	7	1	*14*
	T2 total		14	7	14	20	10	*65*
Type-3	Seasons	spring	–	1	–	2	–	3
		summer	1	–	–	5	6	12
		autumn	1	–	3	–	2	6
		winter	–	3	1	–	2	6
	T3 total		2	4	4	7	10	27
Total			*48*	*27*	*53*	*90*	*55*	*273*

*Refers to a half-decade period.

an average of 9 in the 2010s, and to 11 in the 2019–2023 period, which is examined below in detail. According to surface observations and European reports (e.g., Salvador, P. *et al.* 2022; Cuevas-Agulló, E. *et al.* 2023), the intensity of each event (the amount of transported and deposited dust) also increased during this period. This is confirmed by the increasing frequency of local muddy rain events, which regularly receive considerable media coverage.

A detailed analysis of the dust storm events of the fifth (half)decade of the 45-year database has been undertaken in this article. This included the identification of 55 new episodes between 2019 and 2023. In addition to the increased number of events, it was striking that the occurrence of Type-3 episodes increased significantly, especially in 2022 and 2023. During the five-year period, 10 such episodes were recorded, compared to a total of 17 in the previous 40 years. However, based on surface observations, MERRA-2 Dust Column Mass Density data and dust load data from the BSC operational forecast, there have been changes in intensity in recent years (*Figures 3* and *4*).

Characteristics of some selected events

To illustrate the changing intensity of dust transport and increasing frequency of Type-3 episodes, 11 events were selected *(Figure 5)*, the main characteristics of which are presented in the following:

SDE #1: 23 April 2019.
The most intense and widespread Saharan dust storm event in decades hit Europe in April 2019. By 19 April, atmospheric dust forecast models were already predicting large amounts of dust over the Iberian Peninsula, with a steady supply from the African continent. The cut-off low of 20 April 2019 (a closed circulation system formed from an upper-level trough in the preceding days) determined the synoptic situation of North Africa, and the cyclonic flow lifted a huge mass of desert dust into the atmosphere. The dust-loaded air masses drifted north and northeast (to the western Mediterranean, Spain, southern France and Italy, then towards the Balkans, central and western Europe, the British Isles), and on 23–24 April atmospheric dust was observed over the continent from almost

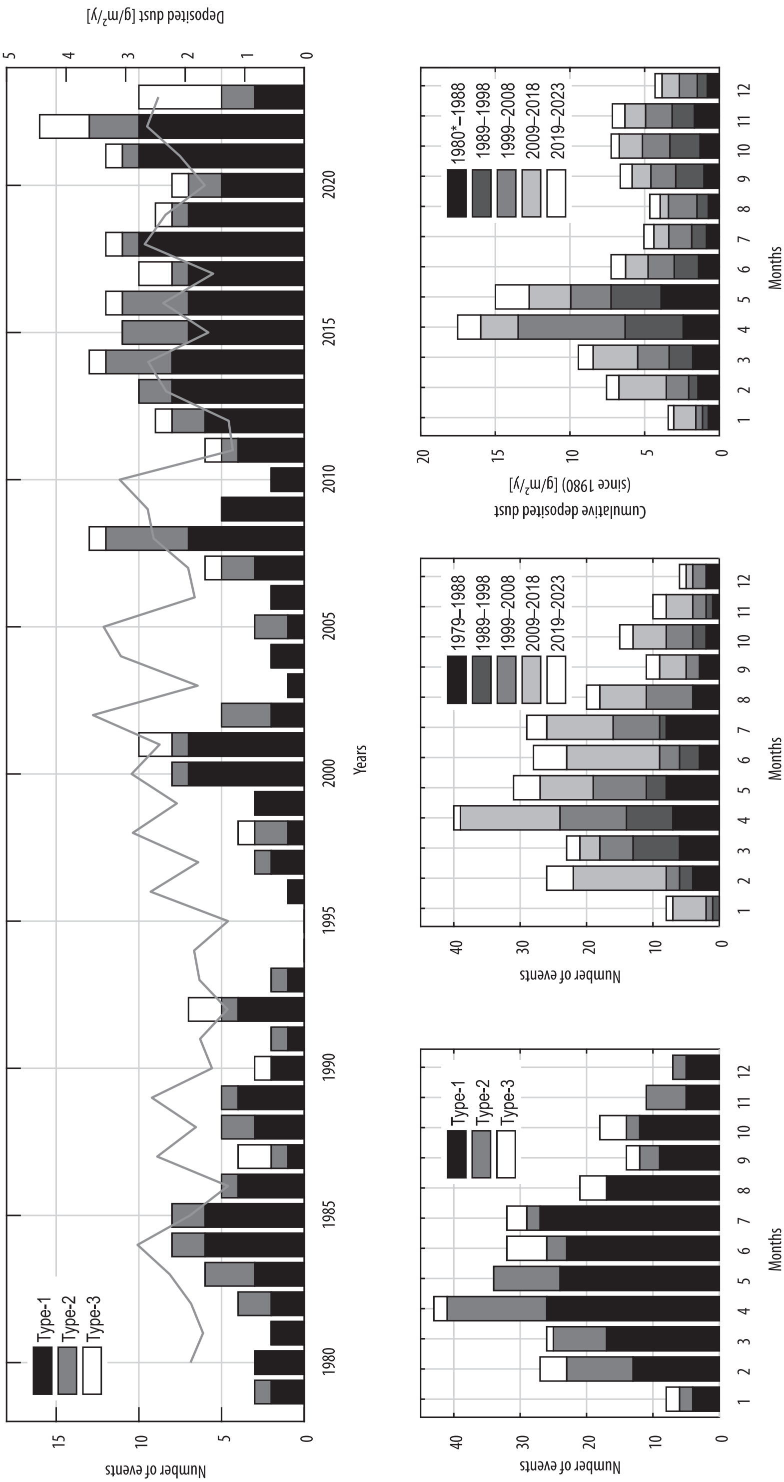

Fig. 2. Frequency of Saharan dust storm events by type and temporal changes in modelled values of deposition in the Carpathian Basin between 1979 and 2023. *Source:* Authors' own elaboration.

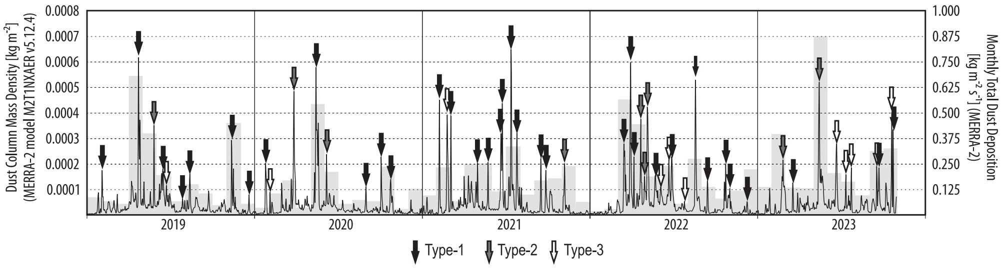

Fig. 3. MERRA-2 daily Dust Column Mass Density and monthly deposition data, and identified Saharan dust storm events by type, 2019 to 2023. *Source:* Authors' own elaboration.

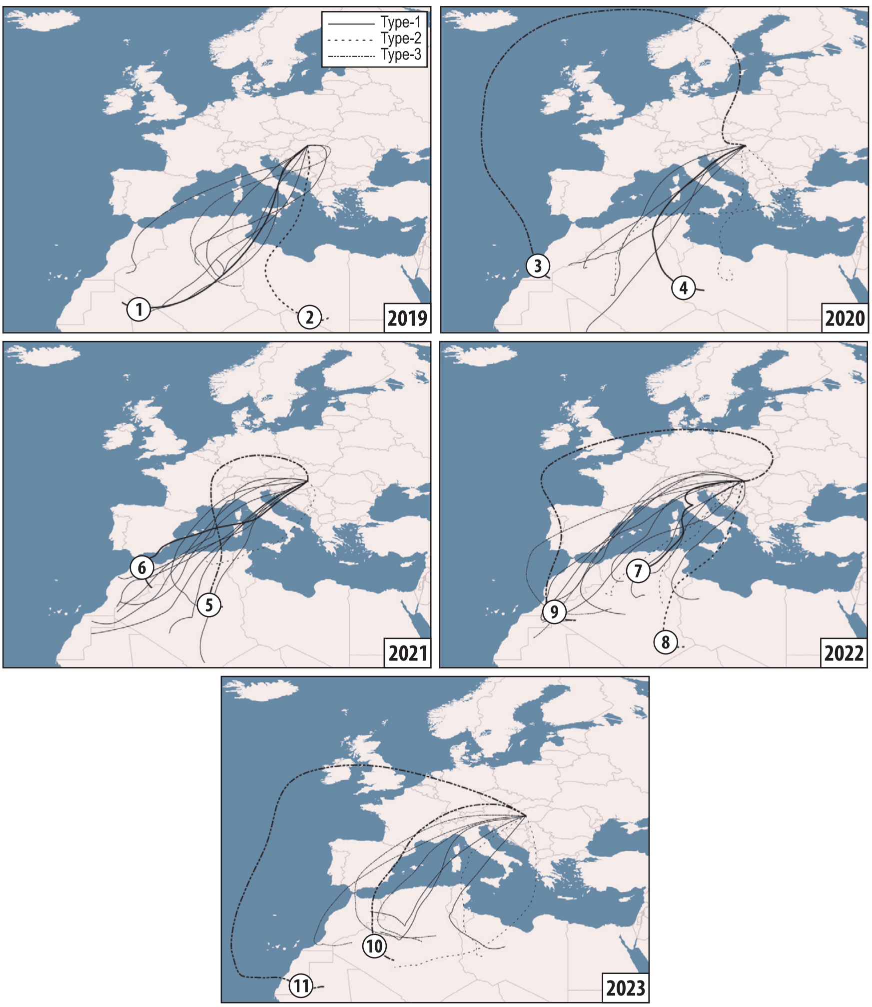

Fig. 4. Dust transport pathways of Saharan dust storm events reaching the Carpathian Basin by year between 2019 and 2023. (Numbered and bolded trajectories of selected episodes are described in the text). *Source:* Authors' own elaboration.

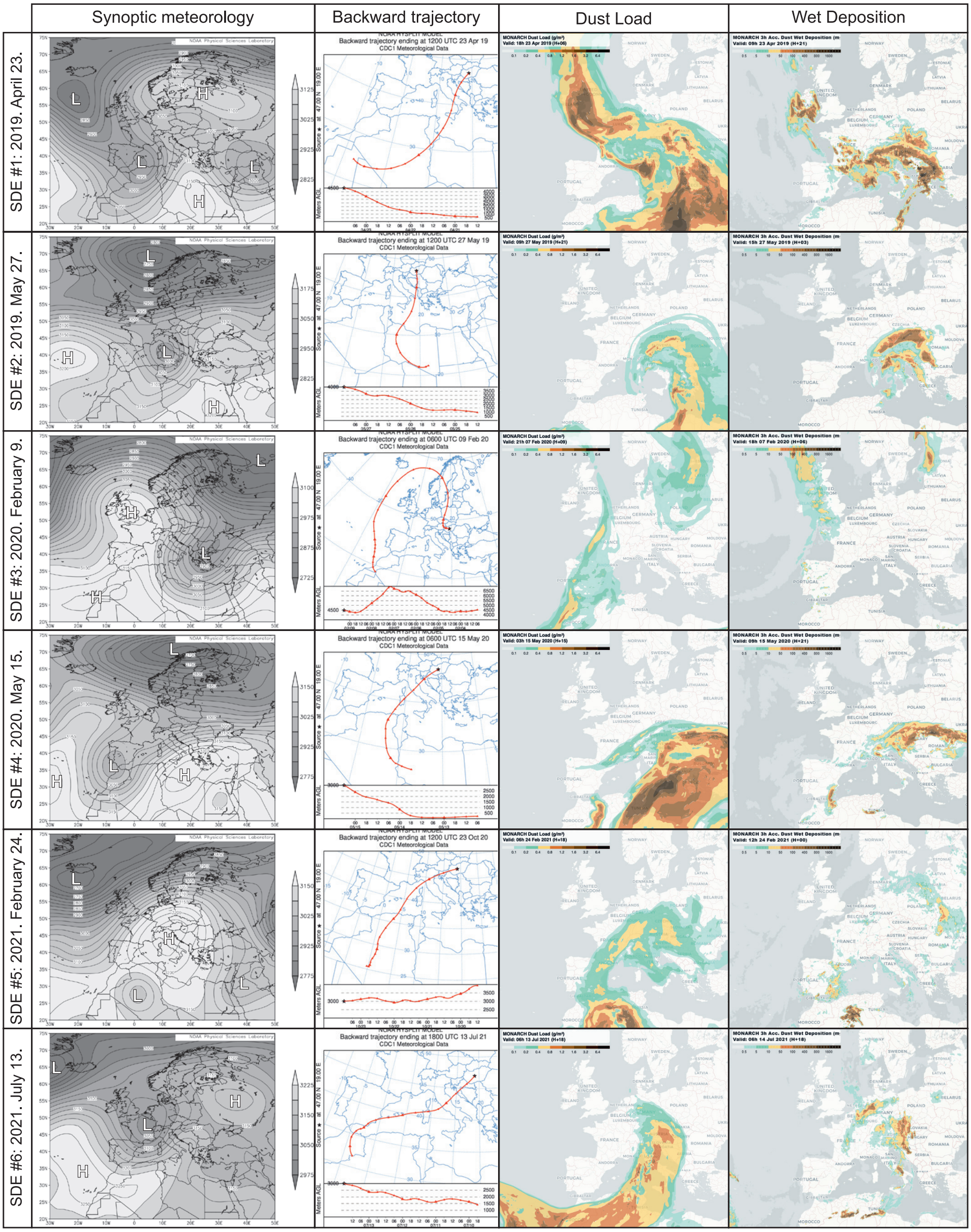

Fig. 5. Synoptic meteorological background (700 hPa geopotential height); backward trajectories of dust-loaded air masses; modelled dust load and wet dust deposition. *Data source:* WMO Barcelona Dust Regional Center and the partners of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) for Northern Africa, the Middle East and Europe.

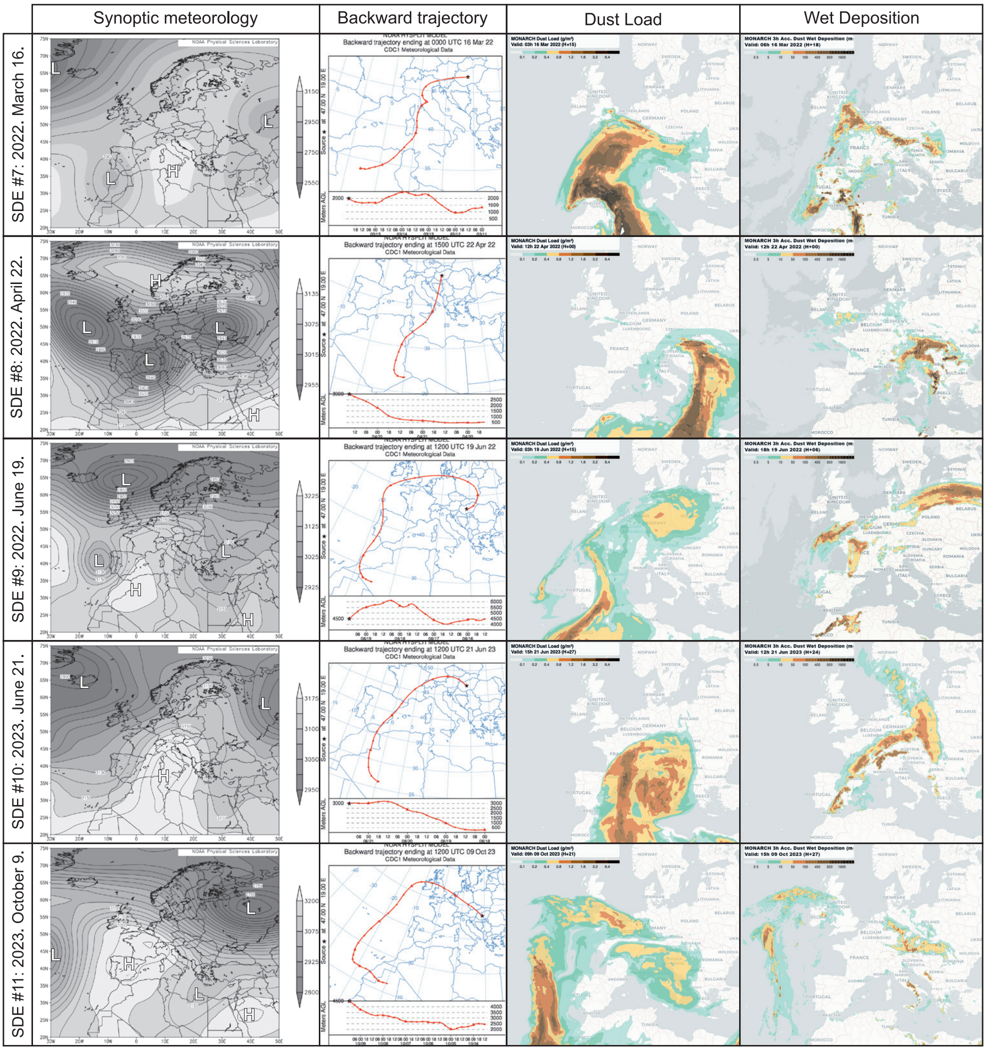

Fig. 5. – Continued.

Iceland to southern Turkey. The meteorological background to the event is a cut-off low resulting from the southward movement of a high-altitude atmospheric trough over the eastern Atlantic basin. The intense southerly flow formed on the foreward side of the eastward moving low pressure plume, which then spread from NW Europe to the eastern Mediterranean Sea due to the blocking effect of the anticyclone over the continent.

SDE #2: 27 May 2019.

The strong southerly flow (meridional wind component above 20 < m/s at the typical dust transport height of 700 hPa) of the foreward side of the cyclone that formed over the western Mediterranean Sea and then deepened over the central sub-basin drifted the Saharan dust over the Carpathian Basin in late May 2019. During the precipitation events associated with the Mediterranean cyclone, large amounts of dust were washed out over central Europe. An extensive cirrus canopy was observed in satellite imagery and in cloud subtype analyses of CALIPSO vertical profiles, the formation of which is assumed to be driven by increased dust concentration and condensation nuclei number.

SDE #3: 9 February 2020.
The transport path of the Saharan dust storm event identified in February 2020 is the longest trajectory identified in recent decades, with desert dust reaching the Carpathian Basin atmosphere after a transport of about 7,500 km. The episode associated with the Western Sahara dust plume initially headed towards the Atlantic Ocean, driven by the clockwise flow regime of a large-scale anticyclone over the southern Iberian Peninsula and the north-western Sahara. Dust drifting over the ocean was carried northwestward by the circulation system of the high-pressure atmospheric object and then moved towards Europe in the westerly wind belt. During this period, the unusually southerly position of the polar jet stream contributed to the formation of several Atlantic depressions and their associated storms, violent cyclones and synoptic situations dominated by meridional wind components. The former Iberian anticyclone led to the formation of a western European omega block, which was of fundamental importance in controlling the direction of dust transport. It should be mentioned that the present episode is also included in the catastrophe of Saharan dust storm events reaching Iceland, as well as the April 2019 episode (Varga, Gy. *et al.* 2021).

SDE #4: 15 May 2020.
Intense dust storms developed in the southern foothills of the Atlas Mountains during the powerful wind gusts of a cold drop from the high amplitude southerly wave of the polar jet stream. African air masses, driven by a southwesterly flow driven by a pressure gradient generated by a frontal trough crossing Europe in a southwesterly-northeasterly direction and a pressure gradient between a southeastern European high-pressure blockage, reached the Carpathian Basin in mid-May 2020. The huge amounts of particulate matter were transported from the southern Atlas foothills, from unconsolidated sediments of its mountain foothills, from the deposits of its intermittent water flows and from the sediments of its salt lakes, which also have a hectic water flow, so from relatively nearby Saharan source areas. Dust deposition has been reported from many countries (Garofalide, S. *et al.* 2022), and the deposited dust was clearly observed on car windscreens, roof windows and other outdoor surfaces.

The particle size of the samples collected from the deposited particulate matter varied over a wide range, with both the finest (fine silt) and sand fractions appearing on the distribution curve, with a mode of 32.6 μm.

SDE #5: 24 February 2021.
The large-scale circulation conditions of the event were determined by a central European atmospheric ridge and the omega blocking situation formed by the troughs on either side. The western trough appeared more prominent on the pressure maps than the eastern one and extended as far northwest as Africa, where a cut-off low was also formed. This meteorological situation persisted for days and in this stationary state the Saharan dust transport over the western Mediterranean basin flowed directly northwards towards higher latitudes. In the atmospheric trough flow regime, the transport of dust at latitudes N50° deviated from the meridional direction and followed the isohips towards the Carpathian Basin. Both the enhanced, above-average meridionality and the extreme amount of dust transport associated with this event have been discussed in detail by Francis, D. *et al.* (2023). Intense dust deposition from southwestern Europe to Finland has created opportunities for citizen science campaigns in many places (e.g., Meinander, O. *et al.* 2023). The results of a highly successful project to collect the dust deposited in the French Alps in connection with the event were published in Dumont, M. *et al.* (2023).

The particle size of the samples deposited in the Carpathian Basin was found to be particularly coarse-grained, with a mode size of 98.2 μm in the distribution curve during our measurements, and smaller particles barely appearing in the sample.

SDE #6: 13 July 2021.
On 9 July 2021, intense dust storms developed in the Tidikelt depression (surrounded by plateaus (Tanezrouft, Plateau du Tademait) and mountains (Ahaggar, Tassili-n-Ajjer), with dust material drifting northwards due to the flow system of a low-pressure atmospheric formation moving eastwards from the Canary Islands. The Saharan dust-loaded air masses were transported eastwards from western Europe by a cyclonic cold front into the central European atmosphere, where an intense washout episode was again observed.

SDE #7: 16 March 2022.
Another Saharan dust storm event affecting almost all of Europe hit our region in March 2022. Images of orange-coloured snowfields in the Pyrenees and the Alps attracted a lot of press coverage, but even in Finland there was significant washout (Meinander, O. *et al.* 2023; Varga, Gy. *et al.* 2023). The synoptic meteorological background of the event was similar to that of the previous ones: the cut-off low from the high-altitude trough, generated by an unusually high-amplitude southern wave of the polar jet stream, caused violent dust storm to pass through the Atlas, with dust material drifting along the northward branch towards the higher latitudes of Europe.

The deposited fine-grained dust samples had a mode size of 12.1 μm, which is the smallest of our Saharan dust samples collected so far.

SDE #8: 22 April 2022.
A powerful cyclone over the Iberian Peninsula advected large amounts of particulate matter into the Mediterranean Sea from the Atlas forelands on 20 April 2022. Two days later, as the low-pressure formation drifted eastwards, its frontal meridional flow brought dust-loaded air masses to the atmosphere of central Europe.

Precipitation-washed particulate matter once again appeared as muddy rain in the Carpathian Basin, with the mode of the samples occurring at 26 μm on the volume-based size distribution curve.

SDE #9: 19 June 2022.
The steep pressure gradient between the cut-off low from the high-latitude trough along the Atlantic coast of the Iberian Peninsula and northwest Africa and the extensive anticyclone that dominates the weather of southwestern Europe was responsible for the atmospheric transport of Saharan dust, which flowed northward in association with the circulation system. The Saharan dust reached the Carpathian Basin along the northern edge of the dissipating anticyclone, with its clockwise flow passing the British Isles, northern Germany and Poland.

SDE #10: 21 June 2023..
The weather of the European continent was dominated by an omega-block low-high-low pressure system with an anticyclonic centre over the central Mediterranean basin. The southerly flow of the western low-pressure system transported particulate matter from the intermountain basins of the Atlas northwards, where the circulation of the northern edge of the anticyclonic system carried air masses towards the Carpathian Basin.

SDE #11: 9 October 2023.
The weather in western Europe and northwest Africa was dominated by a powerful anticyclone in early October 2023. Large amounts of dust were released from the Atlantic coastal West African source areas as a result of localised heavy dust storms, which drifted over the ocean and then northwards. In the North Atlantic region, a series of cyclones deepened and the steep pressure gradient between the prevailing atmospheric pressure regimes allowed the further long-range transport of air masses containing large amounts of dust. Dust also reached the Irish region and then flowed towards Central Europe via northwesterly currents.

Temperature changes during dust storm events

The intrusion of African air masses into the temperate zone necessarily leads to warming. The variability in seasonality, synoptic background, intensity, transport path and frequency of Saharan dust storm events by type all play a role in the observed temperature changes during episodes over time.

During Type-1 SDEs, the major warming effect is mainly observed in autumn and winter, but the average temperature increase is above 1.5 °C in about all seasons *(Table 2)*. Type-2 events associated with Mediterranean cyclones also typically cause above-average warming in autumn and winter, but over the whole period there has been an increase in the spring warming effect on decadal averages. However, just in the last few years, this effect has again been reduced.

In the last five-year period examined in detail, the number of Type-3 events has increased, but the low number of cases means that average effects are not worth talking about for earlier periods. Due to the longest transport path, the warm advection influence of this type could be the weakest, but due to the synoptic meteorological background, i.e., the need for anticyclonic effects in the study area prior to the arrival of dust, a relatively large average temperature increase has been observed in the recent past for summer events.

Granulometric and mineral characteristics

Granulometric analyses of dust samples collected during intense deposition events reveal a high degree of heterogeneity *(Figure 6)*. The particle size of the dust material varies widely,

Table 2. Average surface temperature increase in the Carpathian Basin during the Saharan dust events by decades and synoptic type

Decades	Types	Seasons				Annual mean
		spring	summer	autumn	winter	
1979–1988	Type-1	2.7	1.7	6.6	3.6	2.6
	Type-2	-0.6	–	2.2	2.0	0.8
	Type-3	–	-2.2	2.9	–	0.3
	Decadal mean	*1.6*	*1.4*	*3.8*	*2.5*	*2.0*
1989–1998	Type-1	3.7	3.6	4.4	–	3.8
	Type-2	1.0	–	3.3	–	1.3
	Type-3	9.6	–	–	2.4	4.2
	Decadal mean	*3.1*	*3.6*	*4.1*	*2.4*	*3.2*
1999–2008	Type-1	3.3	3.7	6.6	0.0	3.6
	Type-2	2.0	4.4	5.4	7.4	3.6
	Type-3	–	–	5.7	4.1	5.3
	Decadal mean	*2.8*	*3.8*	*6.0*	*3.8*	*3.7*
2009–2018	Type-1	2.6	3.6	4.8	4.1	3.6
	Type-2	4.4	1.6	5.9	4.6	4.5
	Type-3	2.3	4.0	–	–	3.6
	Decadal mean	*3.0*	*3.6*	*5.1*	*4.3*	*3.8*
2019–2023*	Type-1	1.4	4.0	5.4	6.9	4.1
	Type-2	0.4	1.9	3.1	1.6	1.0
	Type-3	–	3.3	0.3	1.1	2.3
	Decadal mean	*1.0*	*3.6*	*4.5*	*4.8*	*3.2*
Total	Type-1	2.7	3.3	5.4	4.3	3.5
	Type-2	1.5	2.8	4.3	4.0	2.6
	Type-3	4.7	3.2	3.4	2.3	3.2
	Mean	*2.4*	*3.2*	*4.8*	*3.9*	*3.3*

*Refers to a half-decade period.

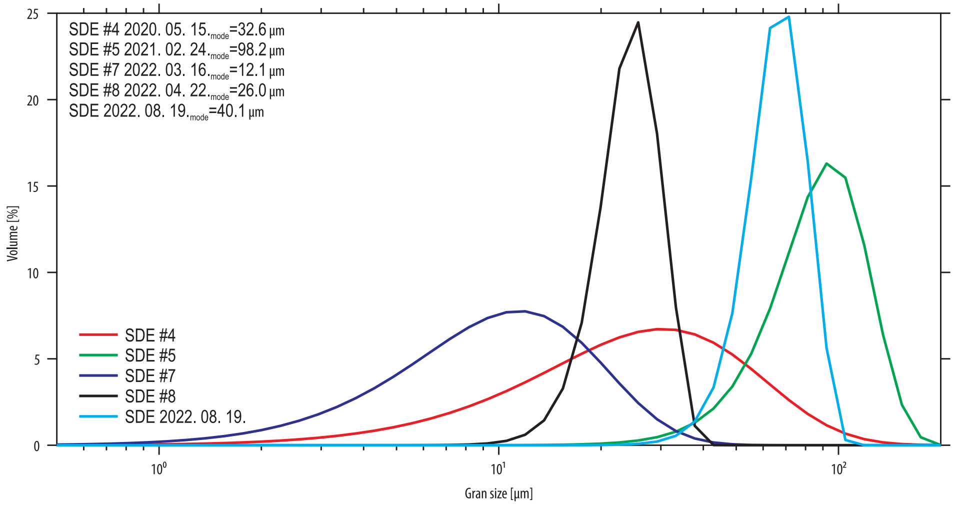

Fig. 6. Grain size distributions of Saharan dust material deposited in Hungary. *Source:* Authors' own elaboration.

with relatively coarse particles often observed, exceeding 20–30 µm. For the samples studied, the modes of the volume distribution curves varied from 12.1 µm to 98.2 µm. In some events, the size distributions spanned a wide range.

This variability was less observed in the shape parameters. Although we have limited the size dependence of the parameters by analysing only the 5–40 µm range, it is still evident that the largest grain size sample of the 24 February 2021 event shows a different character (with significantly smaller convexity and HS circularity values). It is also observed that the dimensionless Intensity mean values, which are also closely related to size and depend on the light transmittance, also vary in a large range (73.4–117.0). Nevertheless, the shape characteristics of the other samples showed very small differences *(Table 3).* The high convexity (0.97–0.98) and solidity (0.94–0.98) parameters clearly support the eolian origin.

Our Raman spectroscopy measurements, which do not provide enough data for detailed mineralogical analysis, identified quartz, feldspar, calcite, dolomite and gypsum in the samples. In addition, other minerals are obviously present in the deposited material, but the technology used is currently not suitable for their detection *(Table 4).*

However, from the information available, it is clear that quartz and feldspars make up the largest proportion of the samples. The number of quartz grains is closely related to the average grain size, with the samples containing the coarsest grains showing the highest number of quartz. In general, it was also observed that gypsum was mainly observed in samples from the Tunisian chotts and the southeastern foreland of the Atlas. However, it is also clear that these mineralogical data do not allow the possible sources to be precisely determined. It is also notable that the sample associated with the strong dust storm event of March 2022, which affected the largest area, was heterogeneous in mineralogical terms, presumably due to the combined emission of several dust sources that were acive at the same time and the mixing of dust material.

Discussion

Changing dust transport mechanisms – the new normal?

We have highlighted in our previous studies that the number and intensity of Saharan dust storm events in Central Europe (Varga, Gy.

Table 3. Shape properties of mineral particles sampled during dust deposition events in Hungary (D[4,3] – Volume Moment Mean – De Brouckere Mean)

Sample name	SDE #4 15 May 2020	SDE #5 24 February 2021	SDE #7 16 March 2022	SDE #8 22 April 2022	SDE 19 August 2022
Aspect Ratio D[4,3]	0.78	0.77	0.77	0.77	0.78
Convexity D[4,3]	0.97	0.86	0.98	0.97	0.98
Elongation D[4,3]	0.45	0.45	0.46	0.45	0.54
HS Circularity D[4,3]	0.81	0.63	0.82	0.82	0.86
Solidity D[4,3]	0.96	0.94	0.96	0.96	0.98
Mean Intensity D[4,3]	77.56	117.00	78.19	73.39	93.47
Intensity STDV D[4,3]	26.85	25.52	23.21	22.40	19.12

Table 4. General mineralogical properties of the Saharan dust samples collected in Hungary

SDE	Quartz	Feldspar	Calcite	Dolomite	Gypsum
	%				
SDE #4 – 15 May 2020	74.7	15.2	6.3	1.3	2.5
SDE #5 – 24 February 2021	85.6	4.1	1.0	9.3	0.0
SDE #7 – 16 March 2022	68.1	10.1	7.2	5.8	8.7
SDE #8 – 22 April 2022	74.1	17.9	5.6	0.6	1.9
SDE – 19 August 2022	75.7	14.3	1.4	4.3	4.3
Mean	*75.9*	*13.0*	*4.4*	*3.8*	*2.9*

et al. 2013; Varga, Gy. 2020; Rostási, Á. *et al.* 2022) has increased in the last 10–15 years. These findings have been confirmed by several other studies across Europe, which also report more frequent (Salvador, P. *et al.* 2022; Cuevas-Agulló, E. *et al.* 2023; Kok, J.F. *et al.* 2023) and intense Saharan dust storm events. It was also striking that North African dust is not only reaching the southern regions of the European continent, but is also becoming more frequent in more northerly regions (e.g., Greenland – Francis, D. *et al.* 2018; Iceland – Varga, Gy. *et al.* 2021; Finland – Meinander, O. *et al.* 2023; Varga, Gy. *et al.* 2023).

This is supported by data from the last five years, which are presented in this article. Both the significantly higher number of events than long-term averages and the changing synoptic background fit well into the context of the previously raised idea that climate change is driving significant changes in atmospheric transport processes. One manifestation of this is the increased warming of the Arctic, i.e. the jet stream pattern modifying effect of Arctic amplification (Francis, J.A. and Vavrus, S.J. 2012). This spatially differentiated warming results in a decreasing temperature contrast between higher and lower latitudes, which difference drives the jet stream, and thus determines its trajectory to deviate more from the west-east flow direction, which is clearly characterized by zonal components, and to become wavier (the role of meridional wind components is increased). In general, a meridional pattern of wind vectors was observed at high altitudes during the intense episodes. The low-pressure atmospheric systems that blew through the Atlas Mountains (driven by the jet), causing severe dust storms there, turned northwards under the influence of the dominant flow and reached central and northern Europe. Similar synoptic situations have been described by Francis, D. *et al.* (2023) for Saharan dust storm events associated with atmospheric river situations in the Alps, which can coexist with severe melting. In another publication (Francis, D. *et al.* 2018), they reported on this meteorological situation in the context of the transport of African dust-loaded air masses reaching Greenland.

This type of increased meridional flow due to climate change will lead to extreme weather events. Atmospheric flows driven by the wavy jet stream cross zones with fundamentally different climatic parameters in their general characteristics, sometimes causing cold spells from the Arctic and, as shown in this paper, warm advection from the hot subtropical climatic zones.

Effects of giant dust transport on mineral dust-related interpretations

The particle size data reported in our observations and measurements also fit well into the range of recent papers on particle size of particulate matter. Previous observations and concepts suggest that the typical grain size of particulate matter reaching Europe (and regions generally further away from source areas) should not be larger than 10–20 μm. As is well illustrated by the European measurement datasets collected by Goudie, A.S. and Middleton, N.J. (2001): Crete: 8–30 μm (mode; Mattson, J.O. and Nihlén, T. 1996), 4–16 μm (median); Spain: 4–30 μm (mean; Sala, J.Q. *et al.* 1996); Germany: 2.2–16 μm (median); Italy: 16.8 μm (modal), 14.6 μm (median; Ozer, P. *et al.* 1998); South France: 4–12.7 μm (median; Bücher, A. and Lucas, G. 1984), 8–11 μm (median; Coudé-Gaussen, G. 1991); France (Paris Basin): 8 μm (Coudé-Gaussen, G. *et al.* 1988); Swiss Alps: 4.5 ± 1.5 μm (median; Wagenbach, D. and Geis, K. 1989); and Central Mediterranean: 2–8 μm (mode; Tomadin, L. and Lenaz, R. 1989). These values are also used as upper bounds in the dust dispersion models (GEOS-5; MACC_II; MASINGAR; MetUM; NGAC; NMMB/BSC-Dust; CHIMERE; CMAQ-KOSA; COAMPS; CUACE/Dust; BSC-DREAM8b; DREAM8-NMME-MACC; TAQM_KOSA – Benedetti, A. *et al.* 2014).

In recent years, the number of papers on long-range transport of large particulate matter has increased significantly, and they report that sometimes 200–300 μm particles can be transported up to thousands of kilometres (Ryder, C.L. *et al.* 2018; Van der Does, M. *et al.* 2018; Adebiyi, A.A. *et al.* 2023). Our reported data also significantly exceed the particle size that was previously considered typical.

This also has a major impact on, for example, the highly underestimated dust deposition data in the models, where the mass of the deposited particulate is related to the third power of the particle size, so a slight upward shift in the size range has a significant impact on the dust flux data (Adebiyi, A.A. and Kok, J.F. 2020). The (paleo)environmental interpretation of the deposition data is thus greatly modified. The importance of eolian dust deposits in climate reconstructions is of particular importance in some regions (e.g., in regions covered by loess). In these data sets, there has so far been no marked inclusion of long-range dust.

Conclusions

In the paper, we completed our previous long-term (1979–2018) analysis of Saharan dust storm events in the Carpathian Basin with an analysis of the period 2019–2023. The 218 dust storm events previously identified for a 40-year period have been complemented by 55 additional events. The number of events over the five-year period was significantly higher than the long-term average, and this fits well with the picture already indicated by the 2010 studies, i.e. that both the number and intensity of dust storm events have increased significantly.

Classification based on the analysis of the synoptic background of dust storm events revealed that the typical meteorological background of these events has been modified. Among the atmospheric flow conditions defined by the wavy jet stream, circulation patterns with a more pronounced meridional wind component were dominant during the more intense dust storm events. It was clearly observed that the dust material was moving further north within the European domain and was also regularly observed in Germany, Poland and Finland. Circulation patterns across climatic belts are also associated with marked weather changes, so that extreme weather events are regularly observed; warm spells, muddy rain and wet washouts during Saharan dust storm events.

Detailed grain size and particle shape analyses of samples of the deposited particulate matter showed that the atmospheric dust material is very diverse. A large amount of coarse-grained fraction was observed in the samples analysed. Among the mineral grains, in some samples, coarse rock flour and sand fractions were dominant. Our knowledge of the long-range transport of this coarse fraction is significantly incomplete, as the range above 20 μm is not even parameterised in climate and dust transport models, i.e. calculations of the amount of transported and deposited dust significantly underestimate the actual values. The data on the long-range transport of large particles also point to the need for revision of (paleo)environmental reconstructions and the role of particulate matter of Saharan origin in sediment and soil formation.

Acknowledgement: The research was supported by the NRDI projects FK138692. This work has been implemented by the National Multidisciplinary Laboratory for Climate Change (RRF-2.3.1-21-2022-00014) project within the framework of Hungary's National Recovery and Resilience Plan supported by the Recovery and Resilience Facility of the European Union. The research was funded by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA). Images were provided by the WMO Barcelona Dust Regional Center and the partners of the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) for Northern Africa, the Middle East and Europe.

REFERENCES

Adebiyi, A.A. and Kok, J.F. 2020. Climate models miss most of the coarse dust in the atmosphere. *Science Advances* 6. Doi:10.1126/sciadv.aaz9507

Adebiyi, A.A., Kok, J.F., Murray, B.J., Ryder, C.L., Stuut, J.-B.W., Kahn, R.A., Knippertz, P., Formenti, P., Mahowald, N.M., Pérez García-Pando, C., Klose, M., Ansmann, A., Samset, B.H., Ito, A., Balkanski, Y., di Biagio, C., Romanias, M.N., Huang, Y. and Meng, J. 2023. A review of coarse mineral dust in the Earth system. *Aeolian Research* 60. 100849. Doi:https://doi.org/10.1016/j.aeolia.2022.100849

Alpert, P., Kishcha, P., Shtivelman, A., Krichak, S.O. and Joseph, J.H. 2004. Vertical distribution of Saharan dust based on 2.5-year model predictions. *Atmospheric Research* 70. 109–130. Doi:10.1016/j.atmosres.2003.11.001

Ansmann, A., Mamouri, R.-E., Bühl, J., Seifert, P., Engelmann, R., Hofer, J., Nisantzi, A., Atkinson, J.D., Kanji, Z.A., Sierau, B., Vrekoussis, M. and Sciare, J. 2019. Ice-nucleating particle versus ice crystal number concentrationin altocumulus and cirrus layers embedded in Saharan dust: A closure study. *Atmospheric Chemistry and Physics* 19. 15087–15115. Doi:10.5194/acp-19-15087-2019

Arimoto, R. 2001. Eolian dust and climate: Relationships to sources, tropospheric chemistry, transport and deposition. *Earth-Science Reviews* 54. 29–42. Doi:https://doi.org/10.1016/S0012-8252(01)00040-X

Atalay, I. 1997. Red Mediterranean soils in some karstic regions of Taurus mountains, Turkey. *Catena* 28. 247–260. Doi:10.1016/S0341-8162(96)00041-0

Barkan, J., Alpert, P., Kutiel, H. and Kishcha, P. 2005. Synoptics of dust transportation days from Africa toward Italy and central Europe. *Journal of Geophysical Research* 110. D07208. Doi:10.1029/2004JD005222

Benedetti, A., Baldasano, J.M., Basart, S., Benincasa, F., Boucher, O., Brooks, M.E., Chen, J.-P., Colarco, P.R., Gong, S., Huneeus, N., Jones, L., Lu, S., Menut, L., Morcrette, J.-J., Mulcahy, J., Nickovic, S., Pérez García-Pando, C., Reid, J.S., Sekiyama, T.T., Tanaka, T.Y., Terradellas, E., Westphal, D.L., Zhang, X.-Y. and Zhou, C.-H. 2014. Operational dust prediction. In *Mineral Dust: A Key Player in the Earth System.* Eds.: Knippertz, P. and Stuut, J.-B.W., Dordrecht, Springer Netherlands, 223–265. Doi:10.1007/978-94-017-8978-3_10

Bücher, A. and Lucas, G. 1984. Sédimentation éolienne intercontinentale, poussières sahariennes et géologie. *Bulletin des Centres de Recherches Exploration* 8. 151–165.

Čanić, K.Š., Vidič, S. and Klaić, Z.B. 2009. Precipitation chemistry in Croatia during the period 1981–2006. *Journal of Environmental Monitoring* 11. 839–851. Doi:10.1039/B816432K

Coudé-Gaussen, G., Désiré, E. and Regrain, R. 1988. Particularité de poussières sahariennes distales tombées sur la Picardie et l'Ile-de-France le 7 Mai 1988. *Hommes et Terres du Nord* 4. 246–251.

Coudé-Gaussen, G. 1991. *Les Poussières Sahariennes: Cycle Sédimentaire et Place dans les Environments et Paléoenvironments Désertiques*. Montrouge, John Libby Eurotext.

Cuevas-Agulló, E., Barriopedro, D., García, R.D., Alonso-Pérez, S., González-Alemán, J.J., Werner, E., Suárez, D., Bustos, J.J., García-Castrillo, G., Garcíia, O., Barreto, Á. and Basart, S. 2023. Sharp increase of Saharan dust intrusions over the Western Mediterranean and Euro-Atlantic region in winters 2020–2022 and associated atmospheric circulation. *EGUsphere* 2023. 1749. 1–39. Doi:10.5194/egusphere-2023-1749

Dumont, M., Gascoin, S., Réveillet, M., Voisin, D., Tuzet, F., Arnaud, L., Bonnefoy, M., Bacardit Peñarroya, M., Carmagnola, C., Deguine, A., Diacre, A., Dürr, L., Evrard, O., Fontaine, F., Frankl, A., Fructus, M., Gandois, L., Gouttevin, I., Gherab, A., Hagenmuller, P., Hansson, S., Herbin, H., Josse, B., Jourdain, B., Lefevre, I., Le Roux, G., Libois, Q., Liger, L., Morin, S., Petitprez, D., Robledano, A., Schneebeli, M., Salze, P., Six, D., Thibert, E., Trachsel, J., Vernay, M., Viallon-Galinier, L. and Voiron, C. 2023. Spatial variability of Saharan dust deposition revealed through a citizen science campaign. *Earth System Science Data* 15. 3075–3094. Doi:10.5194/essd-15-3075-2023

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O. 2000. Climate extremes: Observations, modeling, and impacts. *Science* 289. 2068–2074. Doi:10.1126/science.289.5487.2068

Francis, D., Eayrs, C., Chaboureau, J., Mote, T. and Holland, D.M. 2018. Polar jet associated circulation triggered a Saharan cyclone and derived the pole-ward transport of the African dust generated by the cyclone. *Journal of Geophysical Research: Atmospheres* 123. 11899–11917. Doi:10.1029/2018JD029095

Francis, D., Fonseca, R., Nelli, N., Bozkurt, D., Cuesta, J. and Bosc, E. 2023. On the Middle East's severe dust storms in spring 2022: Triggers and impacts. *Atmospheric Environment* 296. 119539. Doi:https://doi.org/10.1016/j.atmosenv.2022.119539

Francis, J.A. and Vavrus, S.J. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters* 39. 6. 1029. Doi:10.1029/2012GL051000

Garofalide, S., Postolachi, C., Cocean, A., Cocean, G., Motrescu, I., Cocean, I., Munteanu, B.S., Prelipceanu, M., Gurlui, S. and Leontie, L. 2022. Saharan dust storm aerosol characterization of the event (9 to 13 May 2020) over European AERONET sites. *Atmosphere* 13. (3): 493. Doi:10.3390/atmos13030493

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S.D., Sienkiewicz, M. and Zhao, B. 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate* 30. 5419–5454. Doi:10.1175/JCLI-D-16-0758.1

Ginoux, P., Chin, M., Tegen, I., Prospero, J.M., Holben, B., Dubovik, O. and Lin, S.-J. 2001. Sources and distributions of dust aerosols simulated with the GOCART model. *Journal of Geophysical Research: Atmospheres* 106. 20255–20273. Doi:10.1029/2000JD000053

Ginoux, P. 2017. Warming or cooling dust? *Nature Geoscience* 10. 246–248. Doi:10.1038/ngeo2923

Goudie, A.S. and Middleton, N.J. 2001. Saharan dust storms: Nature and consequences. *Earth-Science Reviews* 56. 179–204. Doi:10.1016/S0012-8252(01)00067-8

Harrison, S.P., Kohfeld, K.E., Roelandt, C. and Claquin, T. 2001. The role of dust in climate changes today, at the last glacial maximum and in the future. *Earth-Science Reviews* 54. 43–80. Doi:https://doi.org/10.1016/S0012-8252(01)00041-1

Hoose, C., Lohmann, U., Erdin, R. and Tegen, I. 2008. The global influence of dust mineralogical composition on heterogeneous ice nucleation in mixed-phase clouds. *Environmental Research Letters* 3. 025003. Doi:10.1088/1748-9326/3/2/025003

Hrabcak, P. 2022. Saharský prach nad slovenskom v rokoch 2015–2020 (Saharan dust over Slovakia in the years 2015–2020). *Meteorologický Časopis* 25. 3–17.

IPCC 2022. *AR5 Climate Change 2013: The Physical Science Basis*. IPCC, WWW Document. Available at https://www.ipcc.ch/report/ar5/wg1/

Jackson, M.L., Clayton, R.N., Violante, A. and Violante, P. 1982. Eolian influence on terra rossa soils of Italy traced by quartz oxygen isotopic ratio. *Developments in Sedmentology* 28. 293–301.

Jahn, R., Zarei, M. and Stahr, K. 1991. Genetic implications of quartz in ''Terra Rossa'' soils in Portugal. In *Proceedings of 7th Euroclay Conference.* Eds.: Störr, M., Hennig, K.-H. and Adolphi, P., Dresden, Ernst-Moritz-Arndt-Universität, 541–546.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77. 437–471. Doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Klose, M., Jorba, O., Gonçalves Ageitos, M., Escribano, J., Dawson, M.L., Obiso, V., di Tomaso, E., Basart, S., Montané Pinto, G., Macchia, F., Ginoux, P., Guerschman, J., Prigent, C., Huang, Y., Kok, J.F., Miller, R.L. and Pérez García-Pando, C. 2021. Mineral dust cycle in the Multiscale Online Nonhydrostatic AtmospheRe CHemistry model (MONARCH) Version 2.0. *Geoscientific Model Development* 14. 6403–6444. Doi:10.5194/gmd-14-6403-2021

Kohfeld, K.E. and Tegen, I. 2007. 4.13 – Record of mineral aerosols and their role in the earth system. In *Treatise on Geochemistry*. Eds.: Holland, H.D. and Turekian, K.K.B.T. Oxford, Pergamon, 1–26. Doi:https://doi.org/10.1016/B978-008043751-4/00236-4

Kok, J.F., Ridley, D.A., Zhou, Q., Miller, R.L., Zhao, C., Heald, C.L., Ward, D.S., Albani, S. and Haustein, K. 2017. Smaller desert dust cooling effect estimated from analysis of dust size and abundance. *Nature Geoscience* 10. 274–278. Doi:10.1038/ngeo2912

Kok, J.F., Storelvmo, T., Karydis, V.A., Adebiyi, A.A., Mahowald, N.M., Evan, A.T., He, C. and Leung, D.M., 2023. Mineral dust aerosol impacts on global climate and climate change. *Nature Reviews Earth & Environment* 4. 71–86. Doi:10.1038/s43017-022-00379-5

MacLeod, D.A. 1980. The origin of the red Mediterranean soils in Epirus, Greece. *Journal of Soil Science* 31. 125–136. Doi:10.1111/j.1365-2389.1980.tb02070.x

Maher, B.A., Prospero, J.M., Mackie, D., Gaiero, D., Hesse, P.P. and Balkanski, Y. 2010. Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the last glacial maximum. *Earth-Science Reviews* 99. 61–97. Doi:https://doi.org/10.1016/j.earscirev.2009.12.001

Mahowald, N.M., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S.P., Prentice, I.C., Schulz, M. and Rodhe, H. 1999. Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments. *Journal of Geophysical Research: Atmospheres* 104. 15895–15916. Doi:https://doi.org/10.1029/1999JD900084

Mahowald, N.M., Muhs, D.R., Levis, S., Rasch, P.J., Yoshioka, M., Zender, C.S. and Luo, C. 2006. Change in atmospheric mineral aerosols in response to climate: Last glacial period, preindustrial, modern, and doubled carbon dioxide climates. *Journal of Geophysical Research: Atmospheres* 111. D10. Doi:https://doi.org/10.1029/2005JD006653

Mattsson, J.O. and Nihlén, T. 1996. The transport of Saharan dust to southern Europe: A scenario. *Journal of Arid Environments* 32. 111–119. Doi:https://doi.org/10.1006/jare.1996.0011

Meinander, O., Dagsson-Waldhauserova, P., Amosov, P., Aseyeva, E., Atkins, C., Baklanov, A., Baldo, C., Barr, S.L., Barzycka, B., Benning, L.G., Cvetkovic, B., Enchilik, P., Frolov, D., Gassó, S., Kandler, K., Kasimov, N., Kavan, J., King, J., Koroleva, T., Krupskaya, V., Kulmala, M., Kusiak, M., Lappalainen, H.K., Laska, M., Lasne, J., Lewandowski, M., Luks, B., McQuaid, J.B., Moroni, B., Murray, B., Möhler, O., Nawrot, A., Nickovic, S., O'Neill, N.T., Pejanovic, G., Popovicheva, O., Ranjbar, K., Romanias, M., Samonova, O., Sanchez-Marroquin, A., Schepanski, K., Semenkov, I., Sharapova, A., Shevnina, E., Shi, Z., Sofiev, M., Thevenet, F., Thorsteinsson, T., Timofeev, M., Umo, N.S., Uppstu, A., Urupina, D., Varga, G., Werner, T., Arnalds, O. and Vukovic Vimic, A. 2022. Newly identified climatically and environmentally significant high-latitude dust sources. *Atmospheric Chemistry and Physics* 22. 11889–11930. Doi:10.5194/acp-22-11889-2022

Meinander, O., Kouznetsov, R., Uppstu, A., Sofiev, M., Kaakinen, A., Salminen, J., Rontu, L., Welti, A., Francis, D., Piedehierro, A.A., Heikkilä, P., Heikkinen, E. and Laaksonen, A. 2023. African dust transport and deposition modelling verified through a citizen science campaign in Finland. *Scientific Reports* 13. 21379. Doi:10.1038/s41598-023-46321-7

Monteiro, A., Basart, S., Kazadzis, S., Votsis, A., Gkikas, A., Vandenbussche, S., Tobias, A., Gama, C., García-Pando, C.P., Terradellas, E., Notas, G., Middleton, N., Kushta, J., Amiridis, V., Lagouvardos, K., Kosmopoulos, P., Kotroni, V., Kanakidou, M., Mihalopoulos, N., Kalivitis, N., Dagsson-Waldhauserová, P., El-Askary, H., Sievers, K., Giannaros, T., Mona, L., Hirtl, M., Skomorowski, P., Virtanen, T.H., Christoudias, T., di Mauro, B., Trippetta, S., Kutuzov, S., Meinander, O. and Nickovic, S. 2022. Multi-sectoral impact assessment of an extreme African dust episode in the Eastern Mediterranean in March 2018. *Science of The Total Environment* 843. 156861. Doi:https://doi.org/10.1016/j.scitotenv.2022.156861

Muhs, D.R., Budahn, J., Avila, A., Skipp, G., Freeman, J. and Patterson, D.A. 2010. The role of African dust in the formation of Quaternary soils on Mallorca, Spain and implications for the genesis of Red Mediterranean soils. *Quaternary Science Reviews* 29. 2518–2543. Doi:10.1016/j.quascirev.2010.04.013

Nickovic, S., Cvetkovic, B., Madonna, F., Rosoldi, M., Pejanovic, G., Petkovic, S. and Nikolic, J. 2016. Cloud ice caused by atmospheric mineral dust. Part 1: Parameterization of ice nuclei concentration in the NMME-DREAM model. *Atmospheric Chemistry and Physics* 16. 11367–11378. Doi:10.5194/acp-16-11367-2016

Ozer, P., Erpicum, M., Cortemiglia, G.C. and Lucchetti, G. 1998. A dustfall event in November 1996 in Genoa, Italy. *Weather* 53. 140–145. Doi:https://doi.org/10.1002/j.1477-8696.1998.tb03982.x

Pérez, C., Haustein, K., Janjic, Z., Jorba, O., Huneeus, N., Baldasano, J.M., Black, T., Basart, S., Nickovic, S., Miller, R.L., Perlwitz, J.P., Schulz, M. and Thomson, M. 2011. Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model. Part 1: Model description, annual simulations and evaluation. *Atmospheric Chemistry and Physics* 11. 13001–13027. Doi:10.5194/acp-11-13001-2011

Pósfai, M. and Buseck, P.R. 2010. Nature and climate effects of individual tropospheric aerosol particles. *Annual Review of Earth and Planetary Sciences* 38. 17–43. Doi:10.1146/annurev.earth.031208.100032

Ridgwell, A.J. 2002. Dust in the Earth system: The biogeochemical linking of land, air and sea. *Philosophical Transactions of the Royal Society A* 360. 2905–2924. Doi:10.1098/rsta.2002.1096

Rieger, D., Steiner, A., Bachmann, V., Gasch, P., Förstner, J., Deetz, K., Vogel, B. and Vogel, H. 2017. Impact of the 4 April 2014 Saharan dust outbreak on the photovoltaic power generation in Germany. *Atmospheric Chemistry and Physics* 17. 13391–13415. Doi:10.5194/acp-17-13391-2017

Rodá, F., Bellot, J., Avila, A., Escarré, A., Piñol, J. and Terradas, J. 1993. Saharan dust and the atmospheric inputs of elements and alkalinity to mediterranean ecosystems. *Water, Air, & Soil Pollution* 66. 277–288. Doi:10.1007/BF00479851

Rogora, M., Mosello, R. and Marchetto, A. 2004. Long-term trends in the chemistry of atmospheric deposition in Northwestern Italy: the role of increasing Saharan dust deposition. *Tellus B: Chemical and Physical Meteorology* 56. 426–434. Doi:10.3402/tellusb.v56i5.16456

Rostási, Á., Topa, B.A., Gresina, F., Weiszburg, T.G., Gelencsér, A. and Varga, G. 2022. Saharan dust deposition in Central Europe in 2016. A representative year of the increased north African dust removal over the last decade. *Frontiers in Earth Science* 10. 1–18. Doi:10.3389/feart.2022.869902

Ryder, C.L., Marenco, F., Brooke, J.K., Estelles, V., Cotton, R., Formenti, P., McQuaid, J.B., Price, H.C., Liu, D., Ausset, P., Rosenberg, P.D., Taylor, J.W., Choularton, T., Bower, K., Coe, H., Gallagher, M., Crosier, J., Lloyd, G., Highwood, E.J. and Murray, B.J. 2018. Coarse-mode mineral dust size distributions, composition and optical properties from AER-D aircraft measurements over the tropical eastern Atlantic. *Atmospheric Chemistry and Physics* 18. 17225–17257. Doi:10.5194/acp-18-17225-2018

Sala, J.Q., Cantos, J.O. and Chiva, E.M. 1996. Red dust rain within the Spanish Mediterranean area. *Climatic Change* 32. 215–228. Doi:10.1007/BF00143711

Salvador, P., Pey, J., Pérez, N., Querol, X. and Artíñano, B. 2022. Increasing atmospheric dust transport towards the western Mediterranean over 1948–2020. *Climate and Atmospheric Science* 5. (1): 34. Doi:10.1038/s41612-022-00256-4

Shepherd, T.G. 2014. Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience* 7. 703–708. Doi:10.1038/ngeo2253

Stein, A.F., Draxler, R.R., Rolph, G.D., Stunder, B.J.B., Cohen, M.D. and Ngan, F. 2015. Noaa's hysplit atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society* 96. (12): 2059–2077. Doi:10.1175/BAMS-D-14-00110.1

Tegen, I. and Lacis, A.A. 1996. Modeling of particle size distribution and its influence on the radiative properties of mineral dust aerosol. *Journal of Geophysical Research: Atmospheres* 101. 19237–19244. Doi:10.1029/95JD03610

Tomadin, L. and Lenaz, R. 1989. Eolian dust over the Mediterranean and their contribution to the present sedimentation. In *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*. Eds.: Leinen, M. and Sarnthein, M., Dordrecht, Springer Netherlands, 267–282. Doi:10.1007/978-94-009-0995-3_11

Van der Does, M. Knippertz, P., Zschenderlein, P., Giles Harrison, R. and Stuut, J.-B.W. 2018. The mysterious long-range transport of giant mineral dust particles. *Science Advances* 4. eaau2768. Doi:10.1126/sciadv.aau2768

Varga, Gy., Kovács, J. and Újvári, G. 2013. Analysis of Saharan dust intrusions into the Carpathian Basin (Central Europe) over the period of 1979–2011. *Global and Planetary Change* 100. 333–342. Doi:10.1016/j.gloplacha.2012.11.007

Varga, Gy. 2020. Changing nature of Saharan dust deposition in the Carpathian Basin (Central Europe): 40 years of identified North African dust events (1979–2018). *Environment International* 139. (June): 105712. Doi:10.1016/j.envint.2020.105712

Varga, Gy., Dagsson-Walhauserová, P., Gresina, F. and Helgadottir, A. 2021. Saharan dust and giant quartz particle transport towards Iceland. *Scientific Reports* 11. 11891. Doi:10.1038/s41598-021-91481-z

Varga, Gy., Meinander, O., Rostási, Á., Dagsson-Waldhauserova, P., Csávics, A. and Gresina, F. 2023. Saharan, Aral-Caspian and Middle East dust travels to Finland (1980–2022). *Environment International* 180. 108243. Doi:https://doi.org/10.1016/j.envint.2023.108243

Wagenbach, D. and Geis, K. 1989. The mineral dust record in a high alpine glacier (Colle Gnifett, Swiss Alps). In *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*. Eds.: Leinen, M. and Sarnthein, M., Dordrecht, Springer Netherlands, 543–564.

Weger, M., Heinold, B., Engler, C., Schumann, U., Seifert, A., Fössig, R., Voigt, C., Baars, H., Blahak, U., Borrmann, S., Hoose, C., Kaufmann, S., Krämer, M., Seifert, P., Senf, F., Schneider, J. and Tegen, I. 2018. The impact of mineral dust on cloud formation during the Saharan dust event in April 2014 over Europe. *Atmospheric Chemistry and Physics* 18. 17545–17572. Doi:10.5194/acp-18-17545-2018