Tackling the effects of atmospheric dust hazard on human health

Emmanouil Proestakis
Postdoctoral researcher at the Remote sensing of Aerosols, Clouds and Trace gases (ReACT) research unit of the National Observatory of Athens (NOA) and AXA Research Fund fellow

April 2023, Greece: an impressive cloud of sand from the Sahara invades the skies over Athens

Emmanouil Proestakis is a postdoctoral researcher at the Remote sensing of Aerosols, Clouds and Trace gases (ReACT) research unit of the National Observatory of Athens (NOA) and an AXA Research Fund fellow. His expertise lies in the field of amphoteric aerosols, with focus on the dust component and its related impacts through advanced remote sensing observations, sophisticated techniques, and theoretical models. His recent work led to the establishment of a global and multiyear climate data record of the inhalable component of atmospheric dust, enabling data-driven insight on dust-induced health disorders, with the objective to enhance adaptation, mitigation, and risk management to preserve human health.

What is the contribution of the inhalable component of atmospheric dust to the total aerosol load? How much of it resides close to the Earth's surface, where most human activity takes place? To what extent has it changed over the highly-industrialized and densely-populated areas/Megacities over the last two decades and over which areas is the atmospheric concentration foreseen to exceed the World Health Organization Air Quality Guidelines in the near-future? To what extent have dust emissions changed since the pre-industrial times and what can the national and international initiatives say about the amount of dust that will reside in the atmosphere by the end of the century? The article discusses the current status of pressing societal questions related to the health risk posed by the inhalable component of atmospheric dust, which are made even more pressing by the ongoing climate change. Insights are delivered under the prism of ongoing international initiatives, recent advancements, and the challenging limitations of our capabilities.

INTRODUCTION

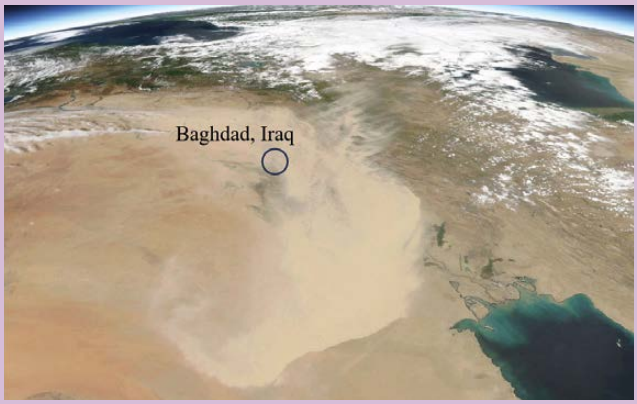
According to the World Health Organization (WHO) and the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC 6thAR), the intensifying climate change represents a major threat to human welfare and health, with adverse socioeconomic impacts. Among the aerosol[1] species, mineral dust plays a key role in the Earth's climate system, affecting anthropogenic activities as well as human health. Recent epidemiological studies report on the strong association between dust and disorders induced on human health, ranging from mild skin irritation to allergic responses, cardiovascular and respiratory diseases, cancer, and even to epidemic outbreaks. Despite the evidence that atmospheric dust constitutes an important environmental risk factor and the international collaborative efforts that have facilitated unprecedented scientific advances, current knowledge is still characterized by large uncertainties, hampering the potential to enhance tailored and high-quality products and services for assessing the dust-related negative impacts on human health. Ongoing international and scientific initiatives need to be strengthened to address better the challenges posed by atmospheric dust, especially under the ongoing climate change.

1 A mixture of particles (= extremely small pieces of matter) and the liquid or gas that they are contained in, that can spread through the air, Cambridge dictionary.

EXPLORING THE DUST-RELATED THREATS TO HUMAN HEALTH

According to Copernicus – the European Union's Earth observation programme – and the World Health Organization (WHO), a remarkable massive dust storm ravaged Iraq in May 2022, resulting in 5000 people hospitalized for respiratory problems due to poor air quality, just in the province of Baghdad ***(Figure 1)***. And while dust hazards of this magnitude are unusual, high concentrations of dust aerosol load are frequently a norm not only over regions in close proximity to the dust sources of the Earth, but also over areas located hundreds – or even thousands – of kilometers downwind, posing a significant threat to human health.

Figure 1: **Iraq engulfed by a sand and dust storm, as observed by the NASA Aqua and Terra MODIS satellite systems between the 15th and 17th of May, 2022**



Source: NASA Worldview

Just in the past year, according to the World Meteorological Organization (WMO) and the released annual Airborne Dust Bulletin report,[2] several intense sand and dust storm (SDS) events affected extensive regions of the globe, such as the Maghreb, the Sahel and the Gulf of Guinea in December 2023, and the broader eastern Caribbean and northern-south America between December 2023 and April 2024. During the same period, in April 2024, southern Europe (particularly Italy and Greece) was completely swallowed by waves of Saharan dust, with dust surface Particulate Matter (PM_{10}) concentrations reaching as high as 200 μgm^{-3} for extensive periods of time, as reported by AtmoHub,[3] the Copernicus Atmospheric Monitoring System (CAMS) National Collaboration Programme in Greece. The reported levels of dust concentrations, though high, were totally dwarfed by the respective extreme mass concentration levels of the severe dust storms that engulfed Mongolia and northern China in March 2023, causing a dramatic decline in air quality for several consecutive days, with PM_{10} concentrations exceeding 9000 μgm^{-3}. It should be noted, as comparative metric, that the adopted WHO Air Quality Guidelines,[4] established in order to provide a worldwide roadmap towards reducing the negative impacts of air pollution on human health, propose ***(Table 1)***:

"A remarkable massive dust storm ravaged Iraq in May 2022, resulting in 5000 people hospitalized for respiratory problems due to poor air quality, just in the province of Baghdad."

***Figure 2*: WHO - Air quality guidelines**

$PM_{2.5}$:	10 $\mu g/m^3$ annual mean
	25 $\mu g/m^3$ 24-hour mean
PM_{10} :	20 $\mu g/m^3$ annual mean
	50 $\mu g/m^3$ 24-hour mean

i. for 24-hour mean particulate matter exposure the upper safety thresholds of 25 μgm^{-3} and 50 μgm^{-3} for $PM_{2.5}$ and PM10, respectively (see definition below).
ii. for annual-mean exposure the upper safety thresholds of 10 μgm^{-3} and 20 μgm^{-3} for $PM_{2.5}$ and PM_{10}, respectively.

It appears that dust events characterized by such exceptionally high concentrations of particulate matter may lead to extremely hazardous conditions, posing considerable challenges to both public life and human health, as reported by several epidemiological studies.[5] However, not all particles composing the aeolian transported dust layers pose the same environmental risk factor. A key aspect governing the association between aerosols, air quality, and the dust-related negative disorders induced on human health is the amount of airborne Particulate Matter (PM) ***(Figure 3)***. In general, PM is divided into three distinct classes, (i) PM_{10} (coarse), (ii) $PM_{2.5}$ (fine), and (iii) UFP (ultra-fine), referring to categories of airborne particles with aerodynamic diameter ≤10 μm, ≤2.5 μm, and ≤0.1 μm, respectively. With respect to mineral dust, large scale intensive experimental campaigns employing airborne in-situ instrumentation (e.g., AER-D/ICE-D campaign in 2015) reported on the size of dust particles residing in atmospheric aeolian transported layers – spanning over more than three orders of magnitude, from less than 0.1 μm (~of the order of SARS-CoV-2 virus) to more than 100 μm (~of the order of a human hair) in diameter.[6] In general, the health risk attributed to coarse-size mineral dust particles is considered low, referring mainly to mild skin irritation or allergic responses, even under conditions of high dust concentrations and long-term exposure. However, dust $PM_{2.5}$ particles – due to their small size – can penetrate deep into the lungs and alveoli, leading to allergic responses, cardiovascular and respiratory diseases, and even cancer. To dive even deeper into the fine-mode dust hazard, the relation between the inhalable component of atmospheric dust and epidemic outbreaks remains an open scientific question, for the role of aeolian mineral dust particles as bacterial carriers, such as in the case of meningitis outbreaks in the Sahel during the Harmattan Seasons, is still elusive.

2 World Meteorological Organization. (2024, July). WMO Airborne Dust Bulletin No. 8. https://library.wmo.int/records/item/68953-no-8-july-2024.

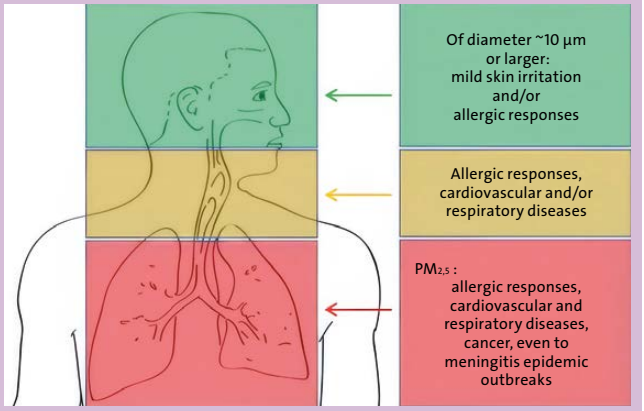
3 *AtmoHUB* - https://atmohub.gr/.

4 World Health Organization. (n.d.). Health impacts of climate change in the WHO European Region (WHO-SDE-PHE-OEH-06-02). World Health Organization. https://www.who.int/publications/i/item/WHO-SDE-PHE-OEH-06-02.

5 Goudie, A. S. (2014). Desert dust and human health disorders. Environment International, 63, 101–113. https://doi.org/10.1016/j.envint.2013.10.011.

6 Ryder, C. L., Marenco, F., Brooke, J. K., Estelles, V., Cotton, R., Formenti, P., McQuaid, J. B., Price, H. C., Liu, D., Ausset, P., et al. (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. https://doi.org/10.5194/acp-18-17225-2018.

Figure 3: Size of dust particles and reported disorders induced on human heal



Source: Emmanouil Proestakis

To better assess the dust-related negative impacts on human health, it is mandatory to enhance our fundamental understanding on the inhalable fine-mode component of dust ($PM_{2.5}$). Towards this objective, it is of high significance to begin with expanding further our basic understanding of the complex life cycle and journey of dust into the atmosphere. This is even more important considering that, in terms of total mass, dust is one of the most predominant types of aerosols encountered in the atmosphere, second only to marine sea salt emissions. More specifically, a recent review quantified and reported the total amount of dust emitted by natural sources (i.e. arid and semi-arid areas) into the atmosphere ~4680 Tg/yr,[7] an amount that would translate to more than 463,000 times the weight of the Eiffel Tower. However, it should be noted that this amount of dust is only a fraction of the total atmospheric dust. At a global scale natural dust sources account for ~75% of dust emissions, with the additional ~25% attributed to anthropogenic activities,[8] such as transportation, infrastructure, building and road construction, deterioration of extended soil surfaces, change in land use, deforestation, grazing, urbanization, and agriculture. Once these thousands of teragrams of dust are released into the atmosphere they are subject to long-range aeolian transport, prior to their removal through wet or dry deposition. Consequently, the frequently dramatic decline in air quality due to increased levels of dust concentration over extensive areas located sometimes even thousands of kilometers downwind from the dust emission sources is a pivotal characteristic of atmospheric dust, elevating the dust hazard from local to regional or even to global scale.

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REGIONAL AND INTERNATIONAL SCIENTIFIC COORDINATION TO FACE CHALLENGES POSED BY ATMOSPHERIC DUST

Nowadays several national and international initiatives have been established with the objective of tackling dust-related problems, since atmospheric dust represents a serious hazard not only for life and health, but also for property, the environment, and the economy and plays a significant role in determining weather and climate systems. For example, the WMO Sand and Dust Storm-Warning Advisory and Assessment System (SDS-WAS), in partnership with the Global Atmosphere Watch (GAW), is a worldwide collaborative cooperation to improve and enhance the capabilities of more reliable operational SDS forecasts. The United Nations Environment Programme (UNEP) Global Environment Outlook (GEO) reports the state and direction of the global environment, including assessments in atmospheric dust sources, trends, and impacts. The Dust Alliance for North America (DANA) consists of an initiative aiming to accelerate the transition of dust-related research into societal solutions. The European Space Agency (ESA), through the Climate Change Initiative (CCI), provides long-term, high-quality climate data records (CDR) derived from satellite observations to support climate research and policy-making, such as the LIVAS CDR.[9] Meanwhile, the European Aerosol Research Lidar Network (EARLINET) operates state-of-the-art stations in Europe -and beyond- to observe and analyze the three-dimensional distribution of aerosols in the atmosphere, including dust.

These indicative initiatives highlight the coordinated actions taken across international organizations, regional groups, and research centers to address the multifaceted challenges posed by atmospheric dust. The collaborative efforts have facilitated unprecedented advances in observational and modelling capabilities of aerosol, which in our times have reached a level of maturity to be ready to translate into user-oriented products and services, helping to shape policies and mitigation strategies. However, more advances still have to be achieved in order to reduce the current scientific uncertainties when it comes to the inhalable fine-mode component of dust, to eventually achieve tailored and high-quality products and services for assessing the dust-related negative impacts on human health. For example, the vast majority of satellite-based Earth Observation (EO) systems today lack the capacity to retrieve and provide the elevation and extension of aerosol layers in the atmosphere, hampering the potential to resolve the aerosol load within the Planetary Boundary Layer, where the main anthropogenic activity takes place. Moreover, most dust-related health disorders depend primarily on the size of dust particles and secondarily on the total mass of dust. However, satellite-based Earth Observations, without extensively applying assumptions and parameterizations, lack the capacity to decouple the dust aerosol component from the total aerosol load, making the retrieval of the inhalable fine-mode component of dust an even more formidable challenge. Finally, today's state-of-the-art atmospheric aerosol models are broadly utilized

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

8 Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., & Zhao, M. (2012). Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Reviews of Geophysics, 50, RG3005. https://doi.org/10.1029/2012RG000388.

9 Amiridis, V., Marinou, E., Tsekeri, A., et al. (2015). LIVAS: A 3-D multi-wavelength aerosol/cloud database based on CALIPSO and EARLINET. Atmospheric Chemistry and Physics, 15, 7127–7153. https://doi.org/10.5194/acp-15-7127-2015.

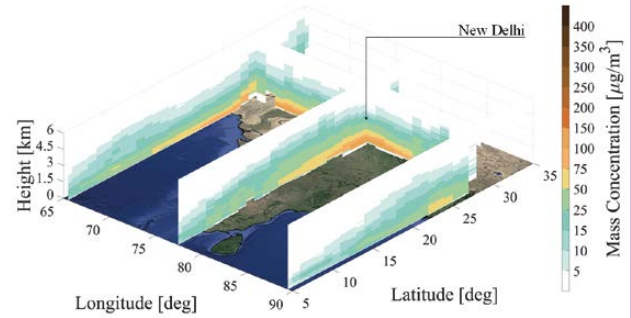
to provide spatiotemporal information on dust emission, transport, deposition and vertical structure. These models typically use static land cover types to classify arid and semi-arid regions as dust emission sources. However, the reliance on empirical emission inventories that do not change over time leads to large uncertainties, especially in regard to unaccounted anthropogenic dust emissions in highly-industrialized and densely-populated regions of the Earth or as feedback from anthropogenic activities (e.g. deforestation of the Amazon Rainforest). This results in considerable underestimations of the amount of dust released into the atmosphere, and thus in assessing the environmental health risks associated with dust.

FUTURE DUST EMISSIONS PROJECTIONS IN THE LIGHT OF CLIMATE CHANGE AND THEIR LIMITATIONS

At this point, it is crucial to highlight that scientific advancements would still be insufficient to achieve ideal adaptation and mitigation strategies on the risks of high concentrations of airborne dust to human health, if they do not take into account one of the most pressing challenges of our era: climate change. More specifically, it is estimated that the global atmospheric dust mass load in modern climate (1981–2000) has increased by approximately 55 ± 30%[10] since pre-industrial times (1841–1860), with observational findings suggesting that anthropogenic land-use change was the key driver for this significant change. This is especially the case for extensive Asian areas, hosting some of the most densely populated and heavily industrialized areas and megacities of the planet, sometimes within or in close proximity to the dust-belt of the Earth. For example, a recent scientific study supported by the AXA Research Fund quantified on the basis of more than a decade-and-a-half of satellite Earth Observations the inhalable fine-mode component of dust (PM_1) over the New Delhi megacity area and close to the surface to be more than 75 μgm^{-3}, translating to concentration levels more than seven times higher than the annual-mean safety threshold for $PM_{2.5}$, as proposed by the WHO in the framework of the Air Quality Guidelines (***Figure 4***).[11] With respect to future dust emissions, projections are highly variable among the climate models, with some of them showing increasing tendencies whilst others show opposing tendencies. Numerous factors of different significance contribute to the apparent discrepancies of climate models' projections, having as a key driver the Shared Socioeconomic Pathways (SSPs) scenarios.[12] More specifically, according to the climate model parametrizations under different socioeconomic trajectories of different possible futures that humanity will face, as established by the Integrated Assessment Modeling (IAM) community in the framework of the Intergovernmental Panel on Climate Change (IPCC) and during the Fifth Assessment Report (5thAR-2013), atmospheric dust load may vary significantly from nowadays.

Despite facing substantial challenges, the global scientific community keeps pushing the boundaries of the current state of knowledge beyond its limitations, translating observational and modelling advances into knowledge, and accordingly into information, tailored products, and end-users' services. A final but highly significant aspect to be enhanced is the coordination between the scientific community, society, and policy makers. An improved flow will amplify information and knowledge exchange between the involved communities, across multidisciplinary and fractured socioeconomic and political sectors, and across cultural boundaries. This improved flow will further assist policy-makers, stakeholders, and end-users with advanced systems and services, towards their endeavor to support effective adaptation and mitigation strategies to preserve human health in the face of climate change.

Figure 4: Atmospheric dust - PM_1 (annual mean: 2006-2022)



Atmospheric dust PM1 over the Indian Subcontinent, with focus over the New Delhi megacity urban area.
Source: Proestakis et al., 2024[13]

CONCLUSION

Atmospheric dust layers, composed of mineral particles of size ranging from less than 0.1 µm to more than 100 µm in diameter, play a key role in Earth's weather and climate systems. These layers come with adverse socioeconomic and environmental impacts, while significantly affecting anthropogenic activities and human welfare, health, and life. Towards addressing the multifaceted challenges posed by atmospheric dust, several national and international initiatives are established, with the collaborative efforts facilitating unprecedented advances in observational and modelling capabilities of dust aerosol. However, despite the evidence that the inhalable fine-mode component of dust is an important environmental risk factor for human health, current knowledge is still characterized by large uncertainties, hampering the potential to reach a significantly higher level of user-oriented products and services that would help shape policies and mitigation strategies. While international initiatives strive to tackle the issues posed by dust emissions, individuals can also take proactive steps to safeguard their health. For those with pre-existing conditions, such as heart or lung disease, monitoring air quality indexes allows them to adjust their daily activities, reducing outdoor exposure or avoiding strenuous exertion when particle levels are high. By combining scientific advances, large-scale mitigation efforts, and individual actions, we can build more resilient communities better prepared to face the challenges of climate change.

10 Indicates the uncertainty range around the estimated increase of 55%. It means that the actual increase in global atmospheric dust mass load could be as much as 85% (55% + 30%) or as little as 25% (55% - 30%).

11 Proestakis, E., Gkikas, A., Georgiou, T., Kampouri, A., Drakaki, E., Ryder, C. L., Marenco, F., Marinou, E., & Amiridis, V. (2024). A near-global multiyear climate data record of the fine-mode and coarse-mode components of atmospheric pure dust. Atmospheric Measurement Techniques, 17, 3625–3667. https://doi.org/10.5194/amt-17-3625-2024.

12 Climate change scenarios of projected socioeconomic global changes up to 2100 as defined in the IPCC Sixth Assessment Report on climate change in 2021.

13 Proestakis, E., Gkikas, A., Georgiou, T., Kampouri, A., Drakaki, E., Ryder, C. L., Marenco, F., Marinou, E., & Amiridis, V. (2024). A near-global multiyear climate data record of the fine-mode and coarse-mode components of atmospheric pure dust. Atmospheric Measurement Techniques, 17, 3625–3667. https://doi.org/10.5194/amt-17-3625-2024.