The Saharan dust plume: Current knowledge on the impact on health, human activities, and the ecosystem, with comments on research gaps

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ABSTRACT

A massive amount of dust estimated at a million tons is released from the Sahara Desert each year into the atmosphere and travels over the North Atlantic Ocean, commonly referred to as the Saharan dust plume (SDP). With its ability to travel over very long distances across the sea, the SDP is of enormous global importance, affecting climatic processes, and playing a significant role in nutrient cycles, sedimentary cycles, and soil development. On the other hand, from an environmental health perspective, the SDP degrades air quality, posing serious health threats to humans, especially to people with lung conditions. Recent literature documents health issues, including respiratory and cardiovascular diseases and even death in extreme cases. Despite this knowledge, large uncertainties exist in our ability to predict future trends in Saharan dust emissions and model-projected atmospheric circulation patterns. Employing a comprehensive search of the recent literature, this study reviews present knowledge of the sources, composition and propagation dynamics of the SDP and the impact of its contained atmospheric particulates on health, ecosystems, and human activities to be

able to formulate credible mitigation measures and unveil areas where further research is needed for improving on these formulations. A comprehensive list of the more recent references (mainly post-dating 2010) is assembled to aid the search process of those wanting to contribute to filling these important knowledge gaps.

Keywords: Sahara dust; human and ecosystem health; nutrient source; addressing the issues

INTRODUCTION

The air is an essential environmental resource for the survival of all life on earth. It is also a means of transportation of airborne pathogens, infections, and particulate matter (PM) (El-Salamony et al., 2021; Stetzenbach, 2009). Hence, air quality plays a crucial role in the global health of humans. The World Health Organisation (WHO) regards air pollution as a top risk to global health (WHO, 2016). Dust particles play a major role in climate systems, too (Ramírez-Romero et al., 2021). Although there are reports of about 1.4% of deaths from exposure to health-damaging effects of PM across the globe (Kotsyfakis et al., 2019), the beneficial effects of mineral dust in the climate system are quite significant (Ramírez-Romero et al., 2021). This is because of their ice-nucleating ability (Ladino et al., 2017), capacity to regulate radiative forcing and act as cloud condensation nuclei (Kanji et al., 2017). Mineral dust of African origin is globally considered a major source of atmospheric particles contributing about 70 % of the world's essential dust (800 Tg yr $^{-1}$) for the balancing of the climate system (Huneeus et al., 2011; Ryder et al., 2019). Meanwhile, as a component of PM, Saharan dust is respirable and could increase the risk of respiratory and related illnesses, often leading to mortality as described by Kotsyfakis et al. (2019). The deadly effect of atmospheric dust has emerged as a global health concern (Kotsyfakis et al., 2019) and has spurred interest among researchers to investigate the risks as tons of dust are transported from

Africa to the Atlantic Ocean through the Saharan Air Layer annually (van der Does et al., 2016). Saharan dust is also a carrier of toxic biological agents including a few microorganisms (Griffin et al., 2001; Kellog and Griffin, 2006; Rodriguez-Gomez et al., 2020), such as fungi, bacteria and viruses, capable of causing disease in a range of organisms, such as trees, crop plants and animals as well as human. A thorough review of pathogenic microorganisms dispersed in desert dust and their implications for agriculture is given by Gonzalez-Martin et al. (2014).

Although little is known about their temporal and spatial variability in the microbial biodiversity in transoceanic dust plumes, or the effect on the deposition environments (Schuerger et al., 2018), there is evidence of their linkage to different kinds of diseases such as brain, lung, cerebrovascular, cardiovascular, and respiratory disorders (Alessandrini et al., 2013; Prospero et al., 2014; Pu and Jin, 2021; Venero-Fernández, 2016; Wilker et al., 2015; Zhang et al., 2016). A good understanding of the effects of the SDP on human activities, health and entire ecosystems coupled with its sources, composition and propagation dynamics would help in the development of protective policy frameworks to reduce mortality and morbidity rates due to dust pollution.

Air pollution by dust has generated an enormous amount of interest in dust research around the world in various disciplines such as air chemistry, fluid dynamics, ocean biology, geomorphology, geology, and meteorology (Shao et al., 2011). Many studies such as those by Mallone et al. (2011); Sajani et al., 2011); Perez et al., (2012); Tam et al., (2012) and Neophytou et al., 2013) have reported relationships between dust plumes and morbidity/mortality. The focus of the present review is on a thorough and updated synthesis (largely based on post-2010 literature) of the effects of SDP on human health, human activities and the entire ecosystem, following elucidation of the sources, composition and propagation dynamics of the plumes.

The air is a crucial resource on which life on earth depends. Thus, air quality is of major global concern (Chen et al., 2022; Kok et al., 2023). Thorough knowledge of the behaviour of dust plumes from the Sahara Desert and other sources is vital for governments and other stakeholders globally because of the increased budget allocation towards improving healthcare systems to cater for increasing health problems associated with air pollution. It is important to highlight the effect of Sahara dust plume on water bodies as well, as the health of water bodies directly or indirectly impacts human existence and quality of life. Finally, for proper mitigation planning to be made, it is necessary to chart the fate of particles in the storm, as this can have a positive effect, such as in fertilizing plant and ocean life, but also a negative effect on arable lands, such as in reducing crop yields by burial of seedlings under dust deposits. Despite the prolificity of papers on the impacts of *in-utero* pollution exposure on early-life health, our article makes additional contributions to this literature. We provide a comprehensive and updated overview of acquired knowledge and point out missing gaps in several important areas of Saharan dust research.

VALUE-ADDED CONTRIBUTIONS MADE

Despite the existence of a large and growing body of research on the various aspects of SD, there are many unknowns in critical aspects of the current knowledge base. A thorough understanding of these aspects is important for aiding the formulation of credible mitigation measures for medical ailments and other maladies resulting from SD transport and deposition. This article presents an updated précis (up to the year 2022) of critical aspects of the SD plume and identifies gaps in knowledge that need urgent research attention for aiding the prescription of intervention measures. It also presents a robust framework for researchers wanting to contribute towards bridging these knowledge gaps and gives recommendations on the directions along which such research should proceed.

METHODOLOGY

The literature search was conducted on electronic databases such as Google Books, Google Scholar, Scopus, and Web of Science. The search has involved the use of several terms and free text words (which include 'Sahara dust effect on health', 'Sahara dust and climate change' and 'Sahara dust effect on the marine body') appropriately combining them. Each of the identified articles was independently reviewed to determine eligibility and to extract study information.

CAUSES OF DUST STORMS

The causes and effects of sand and dust storms have recently been summarized by Opp et al. (2021). Desert lands and sites with low vegetation coverage such as dunes, dry lakes, riverbeds and soil surfaces, are considered principal source areas of sand and dust storms. A gust front or other strong wind blows fine loose particles from a dry surface and transports them by *saltation* and suspension, a process that moves the soil from one place and deposits it in another. The process of *saltation* (a specific type of particle transport by fluids) was earlier identified by Shao et al., (1993) as dominant in initiating (through the bombardment of the surface) the entrainment and subsequent transport by suspension of smaller particles. Most dust storms are natural events but can be aggravated by climate change, land degradation, drought and unsustainable management of land and water resources (UNEP, 2016). Dust storms are often caused by thunderstorms, or strong pressure gradients accompanying cyclones, which increase wind speed over a wide area (Terradellas et al., 2015). The strong winds lift large quantities of sand and dust from exposed, dry soils into the air, and transport them farther away (Terradellas et al., 2015). In early 1970, the quantities of North African dust transported to the Caribbean significantly increased, an increase attributed to the drought in the Sahara region (Prospero and Lamb, 2003). Similarly, more recently (13 October 2022), a new Saharan dust storm crossed the Atlantic Ocean and headed towards the Caribbean, the dust cloud engulfing the skies of Cape Verde (Fig. 1), as captured by one of the Copernicus Sentinel-3 satellites.

LOCATION OF SOURCE AREAS

A recent study by Gini et al. (2022) evaluated the importance of determining the contribution of SDP sources in terms of overall mass contribution, composition, size distribution and inhaled dose. Following long periods of investigation, the actual locations of the source areas of Saharan dust were, until recently, not known with certainty, but earlier data from the Total Ozone Mapping Spectrometer (TOMS) estimates point to two likely major source areas, These are Bodélé depression, and an area covering eastern Mauritania, western Mali, and southern Algeria (Goudie and Middleton (2001). Both major dust sources identified were considered to be driven mainly by natural factors since they appear to be little affected by anthropogenic activities. This is based on several lithogenic tracers (geochemical and radiogenic Sr-Nd-Pb isotope proxies) as well as on the geological subdivision of North African geological provinces, Guinoiseau et al. (2022) have defined six potential source areas (PSA), *viz*.: Libya-Algeria-Mali (PSALAM), Libya-Egypt (PSALE), Bodélé Depression (PSABD), Mali Center (PSAMC), West African Coast (PSAWAC) and Mauritania (PSAMa), providing a unique chemical and isotope fingerprint for each PSA.

DUST COMPOSITION

The chemical characteristics of Sharan dust is presented in Fig. 2 according to (Wang, 2015). The importance of gaining accurate knowledge about the physical and chemical properties of the mineral dust is to be able to better explicate dust atmospheric processes, as well as constrain remote sensing observations (See, e.g., (Rocha-Lima et al., 2018). Elucidation of the mineralogy and physicochemical features of Saharan dust particles is helpful in the identification of sources and determination of their biogeochemical, radiative and health effects. It has always been a challenging task (Rodriguez-Navarro et al., 2018) but a breakthrough has now been achieved through a multi-analytical approach.

The mineralogical composition of dust is strongly related to its chemical composition (Kandler and Scheuvens, 2019). Hence, most dust samples show elevated Si (and Al) contents with Si/Al ratios between 1 and 7 for northern African and eastern Asian dust samples (Scheuvens and Kandler, 2014). According to Panta et al. (2022), the chemical and mineralogical composition of dust storms from desert regions has a profound effect on climate, ocean and land ecosystems, air quality, and several socio-economic variables. These authors have also presented detailed information on the composition of freshly emitted individual dust particles along with the quantitative analysis of their mixing state for use in the containment of climate models including mineral species in their representation of the dust cycle.

Such knowledge will also help in the understanding of SDP transportation and deposition processes of relevance in interpreting sedimentary records for climate reconstructions and models for improved prediction of future climate (van der Does et al., 2016). A quantitative overview of the moist deposition of dust particles to Lake Balaton in Central Europe was presented in 2022 by Rostási et al. (2022), who carried out mineralogical and particle size distribution analysis. X-ray diffraction (XRD) analysis of samples taken during the storm events showed the major minerals to be quartz, kaolinite and 10-Å phyllosilicates, in addition to the occurrence of mineralogical markers of arid dust source - palygorskite and smectite - which were identified in most of the samples analysed.

Saharan dust consists of fine particles of mineral dust, with an average size of just five to ten micrometres. They are rather light, and so can rise to very great altitudes in the atmosphere and stay there for days to weeks, such that particle pollution generated in one area can travel hundreds or thousands of kilometres and influence the air quality of locations far from the source (USEPA, 2022). Working in Tenerife (Spain), Kandler et al. (2007) found the average composition of Saharan dust particles to be 64% silicates, 14% sulfates, 6% quartz, 5% high calcium particles, 1% iron-rich (hematite), 1% soot, and 9% other carbon-rich particles (carbonaceous material)

Atmospheric particulate matter

A distinction is commonly made between particles < 10 µm (PM_{10}) in diameter which can penetrate the lungs, and those with a diameter < 2.5 µm $PM_{2.5}$ which penetrate deep lung tissue. The physics of dust transport and deposition is complex, and there are ongoing studies on how these processes can be quantified. Dust transport and spatial distribution are also poorly represented in current global climate models including the Community Atmosphere Model version 5 (CAM5). (Ke et al., 2022) are developing aerosol models to address these issues.

Diverse PM types (desert dust, glacial dust, wildfire ash, volcanic ash, and dust transported between continents) can have abundant respirable particles (<2.5 µm, $PM_{2.5}$) that may contribute to respiratory and related cardiovascular health problems due to their abundance, mineralogy, geochemistry, bio-solubility, and bioreactivity. Cohen et al. (2017) estimated that long-term exposure to $PM_{2.5}$ caused 4.2 million deaths and 103.1 million lost years of healthy life in 2015. Fine, inhalable airborne particles ($PM_{2.5}$) have a high propensity for creating chronic effects, since they are small enough to penetrate the deeper portions of the human respiratory system, and even get into the lungs and bloodstream. Some PM types can irritate dermal, ocular, and respiratory tissues because they contain acutely bio-reactive, caustic alkali minerals or caustic acid minerals. Many PM types contain potentially harmful elements (PHE) that are bio-accessible in the lung or gastric fluids. Oxidative stress and toxicity in the lungs may result from inhalation of a PM that releases Fe, Mn and other redox-sensitive elements either acutely in high concentrations (i.e. bio-soluble iron sulphates and bio-reactive sulphides in mine wastes or coal dust) or chronically in lower concentrations (Plumlee et al., 2013). In their investigation of PM_{10} emissions and concentrations during a dust storm in Western Sahara and transport of the PM_{10} to the Caribbean Sea and the Gulf of Mexico, Qor-el-aine et al. (2022) were able to correlate average PM_{10} concentrations with altitude during the dust storm. Results from these studies showed that the average PM_{10} concentration below the altitude of 100 m during the dust storm was higher than 100 $\mu g/m^3$ in most of the regions such as Dakhla in Morocco, Nouakchott, Adrar and Tiris Zemmour in Mauritania.

AIR QUALITY GUIDELINES

(Gomes et al., 2022) emphasised the importance of integrating indoor and outdoor air quality monitoring systems to achieve automated air conditioning systems capable of efficiently controlling both temperature and air cleanliness. For instance, there have been relatively few studies about desert dust impacts on air quality and human health in West Africa (de

Longueville et al., 2013), despite the region's proximity to the Sahara and this dearth of data is a major constraint on our understanding of the health impacts in this region. The WHO has not set a minimum threshold for atmospheric concentration that would produce no adverse health effects (WHO, 2006), but it still sets acceptable air quality standards. Individual countries usually adopt WHO's limits or set guidelines that are essentially similar to those of WHO. However, these limits are often exceeded, sometimes by several orders of magnitude, during dust storms. The WHO guideline for the maximum acceptable 24-hour atmospheric concentration is a mean of 50 µg per cubic metre for PM_{10} (WHO, 2006).

RADIATIVE FORCING, CONDENSATION NUCLEI AND ICE-NUCLEATING ACTIVITY

The effect of dust on the radiative budget has lately been discussed by several researchers, including (Francis et al., 2023; Grogan et al., 2022; Saidou Chaibou et al., 2020) since this knowledge can help to lower associated uncertainty in climate models. Desert aerosols have an impact on the energy balance of the entire planet. This might happen because of interactions with radiation, clouds, or ecosystems. However, we are still unsure of whether air dust has a net warming or cooling influence on the climate (Kok et al., 2017).

It was recently discovered by Adebiyi et al. (2023) that coarse and super-coarse dust aerosols have a net positive direct radiative effect (warming) at the top of the atmosphere and can alter temperature and water vapour profiles, affecting the distribution of clouds and precipitation. (Fig. 3). Indeed, as (Saidou Chaibou et al., 2020) have found for West Africa, the presence of dust has a considerable impact on the surface energy budget over the Sub-region, suggesting that dust impacts should be considered in more climate studies to increase the accuracy of climate predictions. At temperatures colder than 258 K, mineral dust has been discovered to be one of the atmosphere's most prevalent ice-nucleating particles (INPs; Brunner et al., 2021). However, nothing is known about how abundant and widely distributed INPs are. According to research by Brunner et al., (2021), mineral dust plumes at cirrus heights crystallize into ice at lower altitudes. The leftover particles are left behind after sublimation in dryer air layers and could be pre-activated. Future enhancements to the sample lines of INP counters, according to Brunner et al., (2021), will be necessary to determine whether these particles are pre-activated, producing higher INP number concentrations than they have recorded. Dust aerosols are thought to be the main contributor to atmospheric ice nucleation. While there are case studies supporting this, a climatological sense of the importance of dust to atmospheric INP concentrations and its seasonal variability over Europe is lacking (Hande et al., 2015).

According to Harrison et al. (2022), the ice-nucleating activity of desert dust is also influenced by its mineralogy, which varies markedly between source areas and across particle sizes. The ice-nucleating activity of African desert dust was discovered to be significantly lower than parameterisations based on soil from specific locations in the Sahara or dust sedimented from dust storms by Harrison et al. (2022) from analysis of samples from the summertime marine boundary layer of Barbados taken during July and August 2017. The authors concluded that the activity of dust in Barbados' boundary layer is largely defined by the low K-feldspar content of the dust, which is around 1 %. They propose that the dust they sampled in the Caribbean was from a region in western Africa (in and around the Sahel in Mauritania and Mali), which has a much lower feldspar content than other African sources across the Sahara and Sahel (Harrison et al., 2022).

(Boose et al., 2016) quantified the ice nucleation properties of desert dust in the Saharan Air Layer (SAL), the warm, dry, and dust-laden layer that expands from North Africa to the Americas. The results of these researchers suggest that atmospheric ageing processes in the SAL can lead to an increase in the *ice nucleation efficiency* of mineral dust from the Sahara. (Liang et al., 2021) presented a modelling case study to elucidate the direct radiative impacts of dust on the early development stage of a tropical cyclone (TC), given the inconsistency of results about the impacts of Saharan dust on the development of African Easterly Waves (AEWs), the African Easterly Jet (AEJ), and TCs.

Dust can have a marked effect on the atmospheric radiative balance at regional scales followed by the concentration of condensation nuclei, both of which phenomena can influence climate variability through surface temperature effects and precipitation patterns (Yoshioka et al., 2007). The study by Meloni et al. (2018) showed that it is important to consider spectrally resolved measurements of brightness temperatures (BTs) for better containment of dust IR optical properties and to obtain a reliable estimate of its radiative effects.

Cirrus clouds

Strong mineral dust events produce dusty cirrus clouds, which are thin, wispy clouds of ice crystals that are observed at high altitudes. Most of these clouds have been observed over Europe in connection with baroclinic storms that are infused with dust. We still don't fully understand the microphysics of these clouds, which is crucial for creating climate prediction models. (Seifert et al., 2022) postulated that the dusty cirrus forms through a mixing instability of moist clean air with drier dusty air and contends that the accurate simulation of dusty cirrus formation obviates the linear dependency on mineral dust aerosol optical depth from the bias of the radiative fluxes.

PROPAGATION DYNAMICS OF SAHARAN DUST STORMS

Dust production and atmospheric entrainment combine meteorology and advantageous surface characteristics, facilitating its conveyance in the wind flow. Although linkages between source regions and seasonal Saharan dust channels are poorly understood, SDP propagation directions are well recognized. The Sahara Desert and the Sahel, as well as other parts of northern Africa, are effectively pushed westward, particularly toward the Atlantic Ocean, where it reaches both North and South America (Prospero et al., 2014) and the western to eastern sides of the Mediterranean basin and parts of the European Continent (di Mauro et al., 2019). Though some plumes head northwards towards Europe, others travel eastwards across the Mediterranean to the Middle East (Kandler et al., 2007; Kubilay et al., 2000; Rodríguez et al., 2001). The Bodélé Depression in Chad and the El Djouf Desert in Western Sahara, are currently thought to be the two largest dust-emitting sources in North Africa (Guinoiseau et al., 2022; Prospero et al., 2002). Saltation and auto-abrasion processes are the principal causes of dust suspension from these source regions (Bristow and Moller, 2018). A technique for moving dust to higher altitudes for longer-range transport is rather well understood. Here, the emission is frequently a diurnal phenomenon when powerful low-level jets that have decreased in height throughout the night combine with convective instabilities that have evolved during surface heating in the morning (Todd et al., 2008).

The SDP is known to travel over very long distances, a feature dependent on the dust residence time in the air, altitude, prevailing atmospheric circulation patterns, buoyancy, and dust lifespan. Dust particles larger than 20 μm in diameter (0.2 μm < D < 100 μm) are generally known to remain airborne during long-range transport (Drakaki et al., 2022), typically, along seasonal transport paths (Middleton, 2017).

Dust particles larger than 70 µm would give up to gravitational forces and fall back to the ground about a day after suspension while those less than 70 µm can remain aloft and eventually transported over thousands of kilometres (Mahowald et al., 2014). However, in exceptional cases, some particles larger than 100 µm are found at distances greater than 1000 km from their source (Korte et al., 2017; Middleton et al., 2001; Ryder et al., 2013). This anomaly requires scientific investigation that would help elucidate the mechanisms and dynamics of the atmospheric transportation of large-sized particles of Saharan dust over great distances. The suspended specks of dust in the atmosphere caused by turbulence counteracting gravitations are transported by wind and then interact with solar and terrestrial radiation (Schepanski, 2018). These transportation dynamics determine the atmospheric radiation budget, which is also influenced by the scattering, absorbing, and re-emission of radiation (Schepanski, 2018). According to Venero-Fernández (2016), dust clouds emanating from the Sahara Desert move from the African continent to the cooler, more humid sea air, reaching altitudes of 5 to 7 km and spreading thousands of km. These clouds have been observed with satellite imaging and the naked eye in several parts of the world. They are taken up by the trade winds and carried westward over the Atlantic, reaching the Caribbean Sea in six to seven days and continuing over the Gulf of Mexico (López et al., 2006).

Most observations of SDP trajectory have been made off the west coast of Africa with the westward flow of material over the North Atlantic Ocean being the most well-documented (Middleton and Goudie, 2001). Large dust outbreaks during the summer months appear to be associated with strong convective disturbances that develop over West Africa at about 15 - 20º N and move westward carrying material entrained in Saharan and Sahelian latitudes.

Resultant dust plumes over the North Atlantic are usually associated with easterly waves that emerge from the African coast every 3 - 4 days. The complex structure of easterly waves produces intricate distribution patterns, including northward branches that can transport material to western Europe. Wang and Liu (2014) showed that distinctive hot air plumes are associated with the SDP during their transport across the tropical North Atlantic. These hot air plumes increase environmental temperatures below 5 km altitudes, with a maximum increase of around 2 - km. This leads to an increase in environmental stability below 2 km altitudes and a decrease in ecological stability between 2 and 5 km altitudes. An excellent overview of different dust dispersion models is given by Holmes and Morawska (2006).

SAHARAN DUST DISTRIBUTION AND DEPOSITION

(Lian et al., 2022) recently used a sectional aerosol model (CARMA) coupled with a climate model (CESM1) to investigate the global distribution of dust aerosols, paying particular attention to the vertical distribution of dust. Their results suggested that Saharan, Middle Eastern, and Asian specks of dust make up ~59.7%, 12.5%, 26 and 13.3% of the global annual mean dust emissions, with the remaining 14.5% stemming from scattered smaller dust sources. These authors further concluded that although Saharan dust dominates global dust mass loading at the surface, the relative contribution of Asian dust increases with altitude and becomes dominant in the upper troposphere. The importance of the dust transport and deposition milieu in controlling regional and global biogeochemical cycles can never be underrated; nor can the effect on pathogen dispersal be discounted.

Gutleben et al. (2022) investigated wintertime Saharan dust plumes in the vicinity of Barbados using airborne lidar measurements. The measurements were conducted in the framework of the EUREC^{4}A (Elucidating the Role of Cloud-Circulation Coupling in

Climate) field experiment upstream of the Caribbean Island in January - February 2020. The combination of the water vapour differential absorption and high spectral resolution lidar techniques together with dropsonde measurements aboard the German HALO (High Altitude and Long-Range) research aircraft enabled a detailed vertical and horizontal characterization of the measured dust plumes. (Gutleben et al., 2022) found that while during the summer months, Saharan dust particles are predominantly transported westwards in Saharan air layers (SALs) at altitudes as great as 6 km, Saharan dust transport in the winter months happens at lower atmospheric levels, mineral dust particles being never observed in altitudes higher than ~ 3.5 km. Low-level transport also favours mixing processes of mineral dust particles with other aerosol species like biomass-burning aerosol or marine aerosol. As a consequence, pure dust aerosol regimes were never observed during EUREC^{4}A and mineral dust particles could only be observed in mixed aerosol regimes. At the lowermost altitudes inside the marine boundary layer (MBL), the dust particles were predominantly mixed with marine aerosol. Above the MBL in altitudes from 2 to 3.5 km, the dust particles were mixed with biomass-burning aerosol from fires in West Africa.

Dust deposition is a principal link in the dust cycle. In (Rostási et al., 2022) presented a quantitative assessment of the wet deposition of dust particles to Lake Balaton (Central Europe) with mineralogical and particle size distribution measurements. Based on the results, wet deposition fluxes of dust particles were estimated for the region. (Rostási et al., 2022) concluded that 2016 was a typical and representative year for the decade, with twelve identified dust episodes. The synoptic patterns of the events fit well with the typical meteorological character of the North African dust intrusions with enhanced atmospheric meridionally.

Dust deposition occurs in three primary ways including settling due to the force of gravity, turbulent dry deposition and scavenging of particles in raindrops (wet deposition) (UNEP, 2020). Suspended desert dust poses a threat to several forms of communication, including radio waves and microwaves which pass through the atmosphere. Attenuation brought about by absorption and scattering by dust and sand particles in the atmosphere mars the functioning of terrestrial and satellite communications. Dust storms can disrupt several forms of transport, resulting in an upsurge in accidents in the air and on the ground (Middleton, 2020). Dust deposition affects populations both within and beyond desert areas and can result in numerous undesirable situations, such as drinking water contamination with microorganisms. Similar contamination can occur when dust laden with salts is deposited on soils. Dust deposition can also take place in households and commercial buildings entailing huge clean-up costs.

The Harmattan season in West Africa

The Harmattan season refers to a season in West Africa in which dry and dusty northeasterly trade winds blow from the Sahara over West Africa into the Gulf of Guinea (Britannica, 2019), transporting large quantities of Saharan dust. The Harmattan occurs during the dry season, between the end of November and the middle of March and is characterised by a cold temperature in most places; but can also be hot in certain areas. During this season the subtropical ridge of high pressure stays over the central Sahara and the low-pressure Intertropical (ITCZ) stays over the Gulf of Guinea. Air temperatures during the Hammatan can fall to 9 °C (48.2 °F) in parts of western Africa. The winds are strengthened by a low-pressure centre over the north coast of the Gulf of Guinea and a high-pressure centre located over north-western Africa in winter and over the adjacent Atlantic Ocean during other seasons. As the Harmattan passes over the Sahara, it picks up large amounts of fine dust and sand particles (between 0.5 and 10 microns) which it transports hundreds of kilometres out over the Atlantic Ocean; the dust often interferes with aircraft operations and settles on the decks of ships. Using two decades of data from twelve low-income countries in West Africa, (Adhvaryu et al., 2019) showed that dust carried by harmattan trade winds increases infant and child mortality. The data enabled these authors to investigate differential impacts over time and across countries, finding declining impacts over time, and suggesting adaptation (Adhvaryu et al., 2019). Using results drawn from national-level measures of macroeconomic conditions and health resources, both economic development and improvements in public health campaigns have played a part in this adaptation, with health improvements playing a larger role (Adhvaryu et al., 2019). Using Dakar, Senegal as a case study, the Harmattan period (November - March) often comes with a cloud of the dust cover and leaves the city under a fog that brings visibility down to impossible levels (Asala, 2021). In some parts of Senegal, the fishing industry which provides food and jobs for several families can be severely affected by massive dust plumes during the Harmattan (Asala, 2021). Reductions in visibility because of airborne dust negatively impacts land and air transport (Terradellas et al., 2015). Poor visibility condition is particularly treacherous during aircraft landing and often results in landings being diverted, and departures delayed for safety reasons (Terradellas et al., 2015).

Labour productivity and household incomes are greatly affected during storm events as millions of people are delayed from reaching their workplaces (UNEP, 2016). They can affect national economies by forcing schools and airports to close, disturbing communications as well as supply chains (UNEP, 2020). Dust can scour aircraft surfaces and damage engines as well as impact the output of solar power plants, especially those that rely on direct solar radiation (Terradellas et al., 2015). Dust deposits on solar panels are of major concern for plant operators as it is time-consuming to keep the solar collectors dust-free to prevent particles from blocking incoming radiation (Terradellas et al., 2015). Annually, sand and dust storms cause losses of US$13 billion in the Middle East and North Africa (UNEP, 2020). Sahara dust storms can reduce agricultural productivity by blowing away topsoil and the dust settles on crops, reducing photosynthesis and negatively affecting yields (UNEP, 2020). Early warning, improved monitoring, and international cooperation should be the *sine qua non* for easing or obviating the negative effects of sand and dust storms (UNEP, 2020). Research suggests that tree planting such as the construction of structures similar to 'China's Great Green Wall project' can reduce the rate and force of dust storms (UNEP, 2020).

EFFECT OF SAHARA DUST PLUME ON HUMAN HEALTH

A large and growing body of research has looked at several infections and diseases associated with desert dust. Exposure to dust in the atmosphere can result in conjunctivitis and dermatological disorders, whereas inhalation can result in respiratory illnesses such as silicosis (sometimes referred to as desert lung syndrome). Fine particles of dust can travel thousands of kilometres on the back of desert dust storms, which may also carry pathogens and harmful substances, causing acute and chronic respiratory problems.

Exposure to atmospheric particulate matter (PM) (See Section on: "Atmospheric particulate matter", this article), such as those occurring during Saharan dust episodes, is one of the most important environmental problems due to its adverse effects on human health (Karanasiou et al., 2012; Ostro et al., 2021; Querol et al., 2019). Most studies in the recent literature indicate that the short-term effects of dust storms on important body organs, including the cardiovascular, respiratory, and cerebral systems, lead to the increased incidence of clinical symptoms and severity of symptoms such as decreased lung capacity (Aghababaeian et al., 2021). Several other diseases are linked to desert aerosols. For instance, exposure to desert dust may explain part of the variability in the incidence of Kawasaki disease, which causes an inflammation of the blood vessels that can lead to heart disease (Jorquera et al., 2015).

(Aghababaeian et al., 2021) have examined the health impacts of dust storms around the world to provide an overview of the issue. This study stressed the high public health significance of PM from desert dust and the need to put in place measures for ensuring adequate preparation, response, and mitigation of these hazardous events. Prominent in this review is the contribution of mineral dust from the Sahara found in PM to many of the deleterious health impacts of air pollution. The PM contributes to all-cause and cause-specific mortality and morbidity, and the PM arising from Saharan dust (in particular), contributes to excess all-cause and cause-specific mortality and morbidity, with larger particles being more harmful than smaller particles (Kotsyfakis et al., 2019). However, there are many unknowns regarding the effect of PM on vulnerable patient populations, precise mechanisms of action and variations between regions in both environmental and health effects. Thus, an urgent effort in the continued deeper analyses of this emerging public health issue is required (Kotsyfakis et al., 2019). It was reported that there was a lack of research on the worsening air pollution caused by atmospheric dust in West Africa, an area that is extremely close to the Sahara, the region that contributes the most to the global dust budget (de Longueville et al., 2010).

INFECTIOUS DISEASES

It has long been recognised that infectious diseases spreading through dust dispersion may also be responsible for adverse health effects resulting from dust inhalation, damaging protective mucosae and rendering individuals susceptible to bacterial infection (Terradellas et al., 2015). In addition to the link between Sahara dust and cardiovascular and respiratory diseases (Feng et al., 2019; Gurung et al., 2017; Momtazan et al., 2019), many epidemiological studies have also drawn the link with overall mortality and a range of infectious diseases (Venero-Fernández, 2016), demonstrating their damaging effects on health (Euphrasie-Clotilde et al., 2020). Cardiovascular mortality risk and acute paediatric asthma admissions could be increased by inhalation of desert dust (Domínguez-Rodríguez et al., 2021; Gyan et al., 2005). Díaz et al. (2012) reported the transmission of Saharan dust in Madrid, Spain, lasting nearly a quarter of the time between the years 2003 and 2005, and incidences of cardiovascular effects during the hot season. and respiratory effects during the dry season. Increased occurrences of asthma and lung diseases in humans have also been reported in other parts of the world because of exposure to SDP (Kotsyfakis et al., 2019). The spread of Saharan dust has been linked to the transport of various microbial populations (Venero-Fernández, 2016) and anthropogenic pollutants that can cause an outbreak of infectious diseases (Diokhane et al., 2016; Karanasiou et al., 2012; Woringer et al., 2018) such as meningitis (Weil et al., 2017).

In dryland areas of the Americas, valley fever, an infectious disease is contracted during dusty conditions by the inhalation of spores of a soil-based fungus (*Coccidioides immitis* or *C posadasii*) that become airborne during dust storms (Comrie, 2021).

Bacterial meningitis

Bacterial meningitis is of worldwide occurrence, but Africa remains the most affected continent, especially in the "African Meningitis Belt" (AMB) (Fig. 4) that extends from Senegal near the Atlantic coast to Ethiopia and Somalia on the shores of the Red Sea (Mazamay et al., 2021; Verma and Khanna, 2012). The belt was first proposed in 1963 by Léon Lapeyssonnie of the WHO, who noticed that the disease occurred in areas receiving 300 - 1,100 mm of mean annual rainfall. In this Belt, outbreaks of bacterial meningitis are closely associated with the Harmattan season, but the pathophysiological mechanisms explaining the seasonal dynamic and epidemic occurrence of bacterial meningitis in the Belt are not yet fully understood (Agier et al., 2013; Koutangni et al., 2019; Yarber et al., 2023). Three main bacteria are responsible for causing bacterial meningitis, i.e., *N. meningitidis* (Nm), *S. pneumoniae* and *H. influenzae* type b. According to (Mazamay et al., 2021) Nm serogroup A is regarded as the primary cause of meningitis in the Belt.

(Woringer et al., 2018) observed that the very high burden of disease in the AMB displays regular seasonal hyperendemicity in the form of sporadic, short, but intense, localised epidemics during the late dry season occurring at a small spatial scale (Yarber et al., 2023). The gravity of the situation is re-iterated by Jusot et al. (2017) who emphasised that the Sahel has the world's highest attack rate (10 per 100,000) and case fatality rates (15%) for bacterial meningitis. Many of these people are subsistence farmers and herders, whose lives and livelihoods are shattered by this debilitating disease. Even when the disease is diagnosed early and adequate treatment is started, WHO (2018) reports a death rate of 8 - 15% of patients often within 24 to 48 h after the onset of symptoms or may result in brain damage, hearing loss or disability in 10% to 20% of survivors.

Possible explanations for the impact of desert dust on meningitis epidemics in West Africa (Table 1) have been reviewed (Middleton, 2017). However, several critical aspects of this problem still need to be clarified before credible mitigation measures can be formulated (Yarber et al., 2023).

(Yarber et al., 2023) examined the (1) seasonality and intra-seasonal variability of dust, climate, and meningitis and the (2) quantitative relationships between various dust proxies with meningitis lags of 0 - 10 weeks in Senegal from 2012 to 2017. Their results suggested that desert dust may have a significant impact on the onset to the peak of the meningitis season in Senegal, and re-iterate the critical need for more PM, meteorological, and meningitis measurements in West Africa to further resolve these relationships. Opoku et al. (2022) remarked on the changing nature of the transmission dynamics of the disease and attempted exploitation of robust mechanisms to manage and prevent the disease at a minimal cost in the context of its public health implications, by use of a mathematical model. As a case in point, between January and May 2012, Senegal experienced an increase in meningitis cases during high concentrations of Saharan dust (Diokhane et al., 2016). Reported cases of meningitis increased by 3-fold during the winter and spring of 2012 compared to the same season in 2013 in Dakar, Senegal (Diokhane et al., 2016). Another case in point features the investigation by García-Pando et al., 2014) on the link between wind and dust and seasonal incidences of meningitis in Niger. These authors concluded that the environmental conditions might presage meningitis outbreaks. In other studies, e.g., (Trianti et al., 2017), there were increases of about 38%, 57% and 60 % in cases of asthma, chronic obstructive pulmonary disease, and respiratory infections, respectively, associated with desert dust days.

Stuart (2018) reported the successful introduction of a serogroup A meningococcal conjugate vaccine in sub-Saharan Africa, a success that must however, not distract from the continuing burden of meningitis in Africa.

The spread of microbial communities

In a study to investigate the relationship between the atmospheric microbiome on dust-affected and dust-free days, (Mazar et al., 2016) used modern genomic methods to measure the effects of dust plumes on the airborne microbial community. The study observed an increase in the relative abundance of desert soil-associated bacteria during dust events while that of anthropogenic-influenced taxa decreased. Hence, it was suggested that the capacity of dust plumes to transport bacteria that are attached to dust particles was the cause of this observation (Mazar et al., 2016). Further analysis of the microbial content of African dust events in Italy by Weil et al. (2017) demonstrated the local soil contamination with African dust microorganisms. This showed that dust can move microbial communities from their origin to a new environment (Weil et al., 2017). Similar studies by Fanizza et al. (2018) and Perrone et al. (2018) suggest that microbial communities exist in the toxic waste within desert dust plumes being transported from one region to another. A soil fungus, Aspergillus has been detected in dust samples collected in the Caribbean. Lung infections caused by several species of Aspergillus have also been shown to be a leading cause of mortality in AIDS victims (Shinn, 2001).

EFFECT OF SAHARAN DUST PLUME ON THE ENVIRONMENT, AND EARTH'S CLIMATE SYSTEM

(Parajuli et al., 2022) have given an excellent summary of the effect of atmospheric dust on climate, environment, and life on Earth; and have called for more in-situ measurements and remote sensing observations from satellites to better understand the dust effect on climate, and for the improvement of dust parameterisations based on currently available ground-based and satellite observations. The environmental regulations of the countries from which the dust is dispersed and where it is transported may significantly differ and may present an innovative area of research that could significantly impact public policy and air quality standards (Mallone et al., 2011). Dust particles coated by pollutants act as condensation nuclei for warm cloud formation and 'as efficient ice nuclei agents for cold cloud generation' (Terradellas et al., 2015). The ability of dust particles to play such roles is dependent on their size, shape, and composition, which is in turn dependent on the nature of parent soils, emissions, and transport processes (Terradellas et al., 2015). Dust particles impact the growth of cloud droplets and ice crystals and thus affect the amount and location of rainfall (Terradellas et al., 2015). Dust particles in the air produce a greenhouse effect by absorbing and scattering solar radiation entering Earth's atmosphere and thus reducing the amount reaching the surface (Boucher et al., 2013; Terradellas et al., 2015). Hence, dust particles indirectly impact the atmospheric condition by scattering, absorbing, and re-emitting radiation (Choobari et al., 2014; Schepanski, 2018).

Research shows that African dust influences air temperature (Plocoste et al., 2021; Plocoste and Pavón-Domínguez, 2020) and may also hinder the development of tropical cyclones (Plocoste and Pavón-Domínguez, 2020). In boreal summer, the Caribbean basin frequently experiences African dust outbreaks (Euphrasie-Clotilde et al., 2020; Plocoste et al., 2021). In June 2020, a very intense dust plume named "Godzilla" (Fig. 5), reached the Atlantic Ocean (Domínguez-Rodríguez et al., 2021; Remini, 2020) and aroused the attention of the scientific community as it was the biggest dust storm reported during the second half of the century (Remini, 2020). The dust plume was so large that it covered the Caribbean Sea and darkened the skies of various states in the United States (Domínguez-Rodríguez et al., 2021). Earlier studies have proposed that African dust-Fe plays a crucial role in triggering *red tides*, toxic algal blooms formed along the west coast of Florida (Lenes et al., 2001; Walsh and Steidinger, 2001). Some 2-3 billion tons of fine soil particles move from Africa every year in dust storms, which deplete soil fertility locally, but their effects can be felt in many other parts of the globe (UNEP, 2020). Using a suite of satellite observations, Ridley et al. (2012) estimated that About 218 ± 48 Tg of dust is annually deposited into the Atlantic and calculated a lower estimate for the dust deposited in the Caribbean and Amazon to be 26 ± 5 Tg yr^{-1} and 17 ± 5 Tg yr^{-1}, respectively.

Large increases in the transatlantic transport of African dust have also been considered a significant contributor to the decline in the vitality of the Caribbean coral reefs (Depraetere, 2000; Shinn, 2001; Shinn et al., 2000) The ‘demise of Caribbean coral reefs’ is discussed further in the Section: “Influence of Saharan dust on the marine ecosystem”, this article. In addition to the formation of red tides (Walsh and Steidinger, 2001), trans-Atlantic transport of African dust may also be responsible for the incidence of amphibian diseases (Kellogg and Griffin, 2003), and the decrease of oxygen (eutrophication) in estuaries (Shinn, 2001). van der Does et al. (2016) discuss the sedimentary processes involved in the transfer of tons of mineral dust from the African continent towards the Atlantic Ocean every year, with several direct and indirect effects on global climate.

Saharan dust and climate variability

(Evan et al., 2016) have shown that the surface wind field responsible for most of the variability in North African dust emission reflects the topography of the Sahara, as a consequence of orographic acceleration of the surface flow. Under these circumstances, the correlations between dust and various climate phenomena probably arise from the projection of the winds associated with these phenomena onto an orographically controlled pattern of wind variability. Sediment records from the northwest African margin display high-amplitude changes in African dust deposition on orbital and millennial time scales (Williams et al., 2016), suggesting that dust may have played an important role in past climate and ecosystem changes in the region.

These substantial changes in dust emissions suggest that dust may have played a significant role in amplifying past changes in the African hydroclimate and that the inclusion of accurate dust fields may help resolve the consistent underestimation of past African monsoon variations by climate models (Perez-Sanz et al., 2014).

SAHARA DUST, A NUTRIENT-RICH SOURCE

The position of dust in global biogeochemical cycles invokes several questions regarding the magnitude, distribution, and variation in dust fluxes across the Earth. This has led to numerous attempts to quantify the contributions of dust sources around the globe (Field et al., 2010). Most observers tend to dwell mainly on the negative effects of dust storms. However, long-distance Saharan dust transport in the atmosphere has beneficial effects in terms of fertilising soils far away in the Amazon jungle. Sahara dust is considered a treasured, natural source of a variety of minerals and nutrients to the western Atlantic coast and the rainforests of South America (Sakhamuri and Cummings, 2019). Dust from land disturbed by humans or extreme climatic events, such as drought, may constitute a substantial fraction - perhaps one-third to one-half - of the total atmospheric dust loading (Intergovernmental Panel on Climate Change, 2022; Tegen and Fung, 1995). Model assessments indicate that global fluxes are dominated by the large deserts of North Africa, Asia, and the Middle East (Tanaka and Chiba, 2006).

Saharan dust effect on soils

Every year, mineral-rich dust from North Africa's Sahara Desert is lifted into the atmosphere by winds and carried on a 5,000-mile journey across the North Atlantic to the Americas. Because soil nutrients (e.g., N and P) and organic matter are often associated with smaller soil particles, soil fertility in dust source areas becomes depleted while sink areas are concomitantly enriched (Li et al., 2007). Every year, mineral-rich dust from North Africa's Sahara Desert is lifted into the atmosphere by winds and carried on a 5,000-mile journey across the North Atlantic to the Americas. African dust contains P and other important plant nutrients that help offset soil losses (Prospero et al., 2020). The seasonal deposition of dust rich in soluble Fe and other minerals is likely to affect both bacteria and fungi within the topsoil and on canopy surfaces, and especially benefit highly bio-absorbent epiphytes, such as lichens (Rizzolo et al., 2016). Saharan dust can provide essential macronutrients and micronutrients to plant roots, and directly to plant leaves.

(Rodriguez-Caballero et al., 2022) have combined the currently limited experimental data with a global climate model to investigate the effects of *biocrusts* (biological soil crusts) on regional and global dust cycling under current and future conditions. These authors have concluded that biocrust control on dust cycling and its climate impacts have important implications for human health, biogeochemical cycling and the functioning of the ecosystems, and thus should be considered in the modelling, mitigation and management of global change. Before the present review, several studies had looked at the impact of dust deposition on terrestrial and aquatic nutrient cycling, but with hardly any unanimity on the dynamics of the system. The more recent literature at the time of writing (2022) indicates that in tropical ecosystems with a long legacy of chemical weathering and depletion of soil base cations and P, dust is a major nutrient source (Field et al., 2010; Molina et al., 2019). Koren et al. (2006) have shown that the transport of Saharan dust to the Amazon basin has played an important role in offsetting the losses of bedrock-derived nutrients to leaching. African dust contains P and other important plant nutrients that help offset soil losses and increase Amazonian soil fertility (Prospero et al., 2020). Aerosols from the Sahara Desert carry these minerals by intercontinental transportation, in an episode of crucial importance in the nutrient cycle of the Amazon rainforest, which naturally has low-fertility lands (Rizzolo et al., 2017). Prospero et al. (2020) have characterised and quantified African dust transport and deposition to South America and discussed the implications for the P budget in the Amazon Basin**.**

Iron is an essential micronutrient for plant growth, and its transport might support the Fe-inadequate Amazon rainforest (Rizzolo et al., 2017). The deposition of Sahara dust results in significant Fe bioavailability within the rainforest canopy (Rizzolo et al., 2017). The seasonal deposit of soluble Fe-rich dust and other minerals may support bacteria and fungi both at the topsoil and on canopy surfaces; hence, Saharan dust could be a source of essential macronutrients and micronutrients to plant roots, and directly to the leaves (Rizzolo et al., 2017). Cloud transport of Saharan dust with adequate sunlight would be a medium for the proliferation of microorganisms by providing bioavailable Fe, organic N_2 and simple amino acids which include glycine, proline and valine which are present in Saharan desert dust-enriched rain (Doganay et al., 2009). Saydam (2002) noted that Saharan dust can produce oxalate after exposure to clouds and water. This may be the reason for the observation and suggestion that in-cloud processes could be the principal pathways to the formation of dicarboxylic acids (Yao et al., 2002). After the in-cloud formation of oxalate, various bacteria and fungi attach to the clay minerals through the formation of iron oxalate (Doganay et al., 2009). Saharan dust contains a significant amount of P, too, which is an essential macronutrient to all living organisms and has been shown to have effects on neighbouring and remote ecosystems located within the dust transport paths (Gross et al., 2016). The productivity of the Amazon rainforest is inhibited by the limited availability of nutrients, especially P (Yu et al., 2015).

The Sahara dust could provide about 0.022 (0.006–0.037) Tg of P per year which is equivalent to 23 (7 - 39) g P ha^{-1} a^{-1} to add nutrients to the Amazon rainforest and could prevent P depletion for decades or centuries (Yu et al., 2015). The biological effect of Saharan dust is dependent on the amount and nature of the P of the dust (Gross et al., 2016). The nature and concentration of P around the origin of Sahara dust and the subsequent acid processes in the atmosphere during transportation determine the quantity of bioavailable P supplied to marine and terrestrial ecosystems through Saharan dust (Nenes et al., 2011). Apart from minerals, Sahara dust also transports hydrocarbons, allergens, and microbial compounds from Africa (Sakhamuri and Cummings, 2019).

Despite the negative effects of Sahara dust, its vibrant effect on colourful sunsets and its protective effect from solar radiation and its marine biogeochemical cycling are well appreciated by nature lovers and environmental physicists (Sakhamuri and Cummings, 2019). In the Bahamas, agriculture is noted to rely significantly on African dust accumulation for the formation of red soils often called “pineapple loam” (Shinn, 2001). Dust reaching the Bahamas also carries substantial quantities of Fe, P, and SO_4^{2-} which are key nutrients for ecosystems.

INFLUENCE OF SAHARAN DUST ON THE MARINE ECOSYSTEM

Research has shown a link between the Sahara Desert dust clouds and diseases in marine ecosystems. The movement of some viruses in dust storms between the land and the sea (Hawkins et al., 2019; Suttle, 2005) provides the mechanism for the increasing rates of disease outbreaks in the marine realm. The global productivity of oceanic plankton over glacial time scales may well have been a function of nutrient additions by dust, engendering the uptake of atmospheric CO_2 (Jickells et al., 2005). A study on the Pacific coast of the southern US states found that the seabed was greatly compromised by *Aspergillus sydowii* (a pathogenic fungus that causes diseases in humans), putting the ecosystems and their interaction with human activity at risk (Garrison, 2006). The desert dust, as a nutrient source could have an impact on algal blooms, an important food source for marine life, while desert dust nutrients could also play a role in the unusually large blooms of floating Sargassum seaweed mats in the Caribbean Sea and the Atlantic Ocean along the coastlines of western Africa and Brazil. However, this is a matter of some controversy (UNEP, 2020). As mentioned previously, links have also been found between desert dust and coral reef systems (UNEP, 2020). The health of coral reef systems responds to numerous issues, but the disease has been an important factor in recent worldwide coral reef declines, and some diseases that affect coral reefs are linked to microorganisms carried in desert dust (UNEP, 2020). Dust deposition may impact stress on coral reefs and thus reduce their resistance to other factors that could deteriorate their health (UNEP, 2020). The 1983 Caribbean near extinction of reef-building staghorn corals and the sea urchin Diadema which is vital to the health of coral reefs could be a result of the dispersal of African dust-containing pathogens (Shinn, 2001). The dispersal of dust from North Africa to the western Atlantic Ocean may be the cause of several environmental disasters such as the death of Caribbean corals, amphibian diseases, red tides (not to be confused with the "blood rain effect"), and a decrease in oxygen (eutrophication) in estuaries (Shinn, 2001). The 'blood rain effect' occurs when a dust cloud originating in the Sahara creates a "blood rain" effect whereby high concentrations of red-coloured dust or particles in this cloud combine with rain, giving it a red appearance as it falls.

In the Gulf of Mexico, nutrients supplied by iron-rich Saharan dust are assumed to promote N_2 fixation by the marine cyanobacteria (*Trichodesmium spp*.) which is a source of the biologically usable nitrogen required to sustain harmful algal blooms caused by the toxic marine dinoflagellate Karenia Brevis (UNEP, 2020). Walsh et al. (2006) suggest that the negative effects of Saharan dust have persisted since at least the late 1520s when the Spanish explorer Álvar Núñez Cabeza de Vaca observed that the local indigenous American shellfish harvest was suspended seasonally on what are now Texas beaches.

EFFECT OF SAHARA DUST ON HUMAN ACTIVITIES AND SOCIAL LIFE

The Saharan dust storms (SDS) affect the lives and livelihoods of millions of people globally, causing the loss of some $13 billion in GDP (UNEP, 2020). These storms are becoming more frequent and more intense because of the increase in human activity and long periods of drought in many of the affected regions. (Middleton, 2020, 2017) provides excellent reviews on the effects of Saharan dust on human activities and social life. Some of these effects have also been briefly commented on in the foregoing paragraphs (e.g., under: “Saharan dust distribution and deposition” and “The Harmattan season in West Africa.” During the Harmattan season, we experience a significant rise in the number of road traffic accidents and flight delays, greater risks of wildfires and medical conditions, ranging from respiratory illnesses to skin disorders. Saharan dust increases asthma attacks in children in the Caribbean.

Many gaps remain in our understanding of the relationship between desert dust and the well-being of urban residents. In west Africa, for example, a critical knowledge gap lies in the precise nature of the association between meningitis outbreaks and the dry, dusty atmospheric conditions of the Harmattan (See Section on: “Bacterial meningitis”, this article). Although dust storms do not usually result in the severe destruction of infrastructure and deaths associated with other natural hazards such as tsunamis or volcanoes, the cumulative effects on society can be considerable, largely because dust events occur more frequently than most other hazards. There continues to be worldwide interest in the disruption wrought by desert storms to economic and social activity, including their diverse health effects because dust events are also important for ecosystem functioning (Middleton, 2017) and the eventual attainment of sustainable development goals (UN Secretary General, 2019).

(Middleton, 2017) also presents examples of the several undesirable outcomes of dust in the agricultural milieu. For instance, when material entrained from the soils in agricultural fields gives rise to a dust storm, loss of soil particles, nutrients, fertilisers and seeds occurs leading to severe damage to crops by abrasion. There is decreased productivity in the labour force and earnings at the household level decline steeply during these storms. People cannot reach their workplaces on time, and factories and offices are closed. Desert dust in suspension presents problems for several forms of communication, including radio waves and microwaves which pass through the atmosphere (Middleton, 2017). Dust storms can result in dangers for certain modes of transport and an increase in accidents in the air and on the ground. Poor visibility is a frequent cause, sometimes in combination with the adverse mechanical effects of dust (Middleton, 2017). Although often mentioned in the literature as a transport hazard, aircraft flights in dusty conditions is a relatively under-studied aspect of desert dust. Strong, erosive winds also have impacts on rail communications. (Cheng et al., 2015) reported that direct destructive effects on railways in north-western China resulted from copious airborne particles that can break windows, damage carriages, and even blow over the train, as well as reduced visibility that results in trains being stopped for safety reasons.

Dust deposited on plants can have a range of physical and chemical impacts. Dust deposition in households and commercial buildings requires major efforts and economic costs for interior cleaning and domestic landscaping clean-ups (Qian et al., 2020). Such deposits also reduce reservoir storage capacity and clog streams and drainage channels. Dust deposition can have serious repercussions on the operating potential of solar power plants (Vedulla et al., 2022), adversely affecting the two main technologies used to convert the sun's abundant radiation into electricity, photovoltaic (PV) and concentrating solar–thermal power (CSP) systems. The reliability of power distribution grids in desert areas can also be adversely affected by excessive amounts of dust (Maliszewski et al., 2012). Dust and sand particles that carry an electrical charge interfere with porcelain insulators on high-voltage transmission lines, reducing effective distribution and potentially resulting in flashover outages.

Economic costs

According to (Middleton, 2017), given the importance of desert dust as a hazard to human societies, it is surprising to note that there have been relatively few attempts to assess their impacts in economic terms. The cost of direct and indirect effects of an SD dust episode can be considerable. For instance, consider the most affected socio-economic sectors (e.g., civil protection, aviation, health, and solar energy production). (Monteiro et al., 2022) estimates the cost of direct and indirect effects of the extreme African dust episode in the Eastern Mediterranean in March 2018 to be between 3.4 and 3.8 million EUR for the Greek Island of Crete. Concerning the study of the Sahara Desert Dust Outbreak in the Canary Islands (22 - 24 February 2020), Cuevas et al. (2021) called for atmospheric researchers to work together with specialists from other disciplines to be able to assess the impact that such adverse meteorological events can have on numerous socio-economic activities and to estimate, if possible, their economic cost.

CONCLUSIONS AND RECOMMENDATIONS

The importance of the role of dust in terrestrial and oceanic biogeochemical cycling and its effect on global climatic processes can never be understated. The various interactions are complex and not fully understood. Dust fertilises and sustains both oceans and forests and can cause drought intensification due to changes in the Earth's radiative balance. On the other hand, dust can enhance precipitation by acting as nuclei for raindrops. Knowledge of the mineralogical composition and physicochemical features of Saharan dust particles constitute important data for the identification of source areas and determination of their biogeochemical, radiative and health effects. However, these items of information are not always easy to muster. The transport of dust, both at the regional and global scale, plays many significant roles in the earth's system, influencing phenomena such as climate, nutrient cycling, and human and ecosystem health. Yet this role, to date, remains poorly quantified.

In this paper, we have attempted a review of the more recent literature on the impact of the SDP on ecosystems, human activities, and global health, as a necessary basis for formulating revised mitigation guidelines. In concordance with previous work, our review shows that the SDPs have significantly impacted, and still are greatly impacting, human well-being and ecosystems at large. Some of these impacts are positive but a high proportion of them are negative. The negative impacts of desert dust on humans are beyond health issues, for they can disrupt human activities and thus affect social life. Timeous execution of plans that could bring development to communities and entire countries can be thwarted. Forced cancellation of national events planned to address crucial issues on development and advancement could occur because of the inability of participants to get road and air transport to the venue. There is high-rate mortality resulting from multiple road accidents due to poor visibility during the Harmattan and dust storm season in Africa. Some of the victims of such road accidents are young people such as college and university students, and young professionals who could have contributed to the growth of their various communities.

On recommendations for mitigating the effects of desert dust storms, perhaps the words of Kinni et al. (2022) are instructive: "Future efforts should concentrate on increasing awareness among stakeholders and the public and developing national policies, including effective measures to minimize DDS exposure." More studies that assess the economic impact of sand and dust storms are required, as well as the gathering of more data on the sources, trajectories, and depositions of the storms. Schuerger et al. (2018) listed several science questions and knowledge gaps in researching microbial transport and survival in Asian and African dust plumes that reach North America. These authors also provided a conceptual analysis as an initial framework for evaluating priorities in the rich research landscape of transoceanic dust/microbe transport, survival, activity, ecosystem impacts, and transport modelling. The following recommendations for policymakers are adapted from Middleton (2020);

- Preserve ecosystems, encourage agricultural practices that prevent soil erosion, and use water resources wisely in areas where this issue with global environmental health has anthropogenic roots.
- Conduct evaluations of dust risk and susceptibility as part of the Sendai Framework for Disaster Risk Reduction.
- Reduce exposure to dust and its negative effects by putting early warning systems for public health, forecasting, and monitoring in place.

The following list incorporates some of the more pressing research needs on the diverse impacts of SDPs uncovered in this review:

I. Clearly, the health impact of Saharan dust outbreaks needs to be further researched. Future studies should focus on the chemical characterisation and potential toxicity of coarse particles transported from the Sahara Desert admixed or not with pollutants from anthropogenic sources. This is given the diverse outcomes for PM_{10} and $PM_{2.5–10}$.

II. There is an imbalance in the volume of research on the impact of Sahara dust exposure and health effects in West Africa, a region so close to the Sahara Desert, relative to studies in other affected parts of the world including Europe and the Americas (de Longueville et al., 2013).

III. In West Africa, a critical knowledge gap lies in the precise nature of the association between meningitis outbreaks and the dry, dusty atmospheric conditions of the Harmattan (Middleton, 2020). Much more research on this topic is justified.

IV. Up till recently (2020), the role of local-scale forcing mechanisms such as low-level jets in the June 2020 dust events is still unclear (Francis et al., 2020).

V. More studies involving quantifications are needed such as determining atmospheric radiative and thermodynamic properties of Saharan dust storms (Asutosh et al., 2022) to help us better understand the climate effects of dust and make improvements to dust simulation using appropriate models.

VI. Till recently (2021), the effect of exposure to atmospheric particulate matter-bound polycyclic aromatic hydrocarbons and their health effects remains unclear (Yang et al., 2021).

VII. We still are unable to accurately predict the consequences of harmful algal blooms (red tides) on humans and other vertebrates because of our inadequate understanding of the factors that promote their initiation (Walsh and Steidinger, 2001).

VIII. By using satellites to monitor dust arrivals and toxic algal blooms, we may be better able to predict the onset of red tides, and perhaps close beaches and fisheries well in advance of the event.

IX. Accurate findings on the influence of SDP on the climate are not yet in place, particularly on tropical cyclone activity (Sakhamuri and Cummings, 2019).

X. Evidence on the harmful effects of Sahara dust on plants and animals, especially birds, and erosive effects on the aviation industry is woefully lacking.

XI. The net economic impact of long-distance Saharan dust rides is still imperfectly known.

XII. The more established mitigation measures in semi-arid areas include stabilising soil surfaces through mulching, shrub and tree plantation, windbreaks, and the erection of barriers, such as the use of dead vegetation. Given the limited options available in halting these storms in the short or medium term, we need to consider more deeply, the elaboration of local adaptation and mitigation strategies.

XIII. Satellite monitoring, the setting up of trans-Atlantic air quality surveillance and early warning systems, preparedness, and international cooperation, can go a great way in reducing the impact of dust storms. Reforestation/tree planting can also help reduce the effect of Sahara dust on human health. The potential applications of a Sand and Dust Storm Warning System for agricultural users can never be overstated.

XIV. Public health measures could include notices to especially vulnerable population groups such as the elderly and people with previous pathologies, advising them to limit their exposure in outdoor environments.

XV. The investment of resources in researching the impacts of Saharan dust storms and how to forecast and mitigate them should thus be prioritised at the global level. Early warning, improved monitoring and better preparedness, and international cooperation can help mitigate the impact of sand and dust storms.

COMPETING INTERESTS

The authors have declared that no competing interest exists.

AUTHORS' CONTRIBUTIONS

With the submission of this manuscript, we would like to state that this work is original and compiled by the authors. No part thereof has been submitted nor published elsewhere. All authors agree with the contents of the manuscript and its submission to the journal.

FUNDING INFORMATION

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

DATA AVAILABILITY

Data sharing does not apply to this article as no new data were created or analysed in this study.

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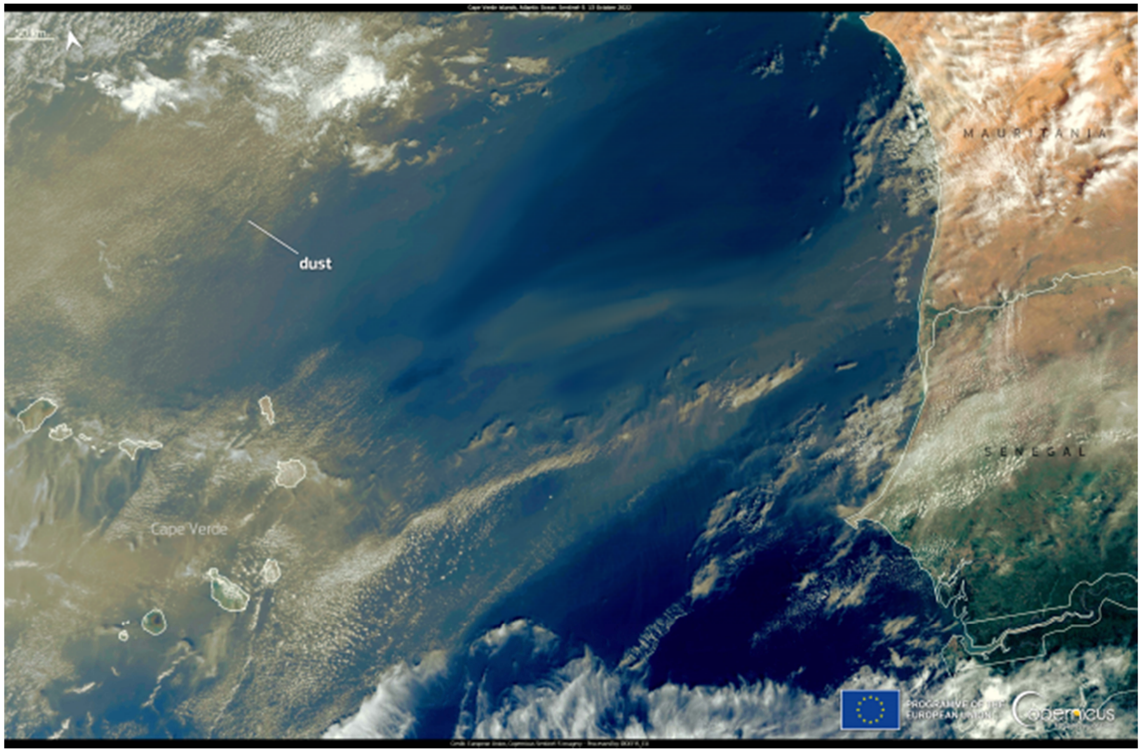

Fig. 1: Saharan dust storm crossing the Atlantic Ocean on 13 October 2022, heading towards the Caribbean, engulfing the skies of Cape Verde. Credit: European Union, Copernicus Sentinel-3 imagery [https://www.copernicus.eu/en/media/image-day-gallery/new-saharan-dust-storm-likely-reach-iberian-peninsula (accessed 04.01.2022)]

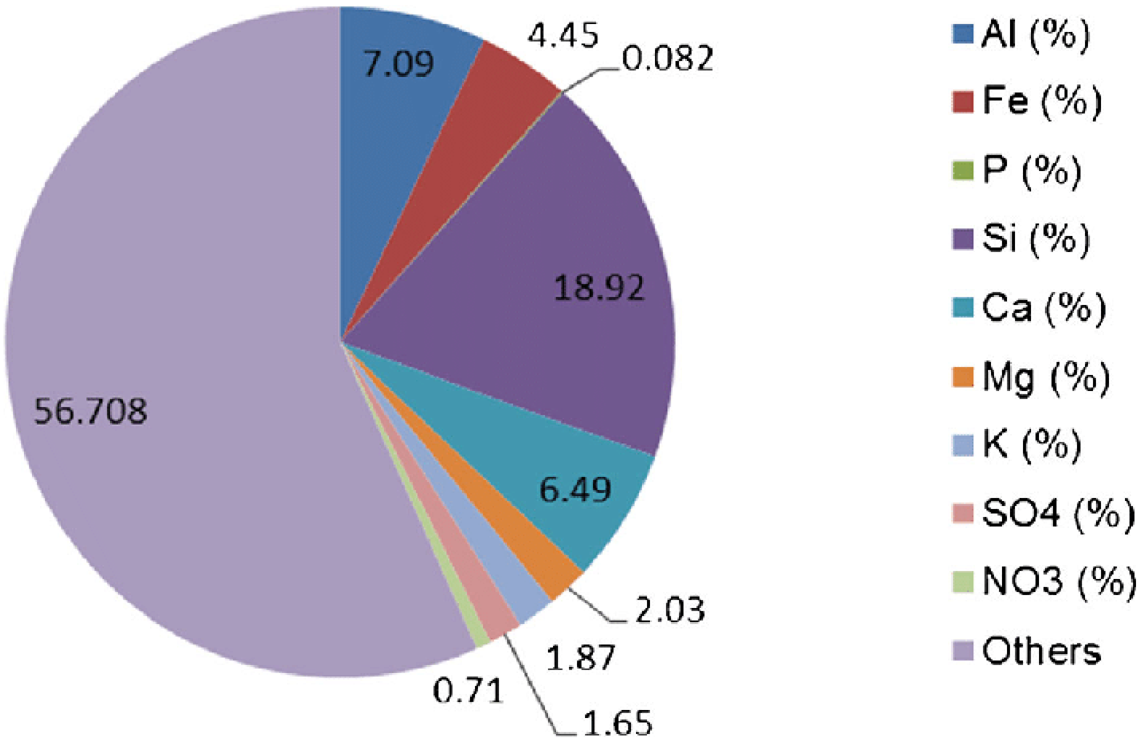

Fig. 2. Chemical characteristics of Saharan dust. Mean percentages of components measured in previous studies (Data source: (Formenti et al., 2003; Guieu, 2002) Credit: Julian Wang. Source: (Wang, 2015)

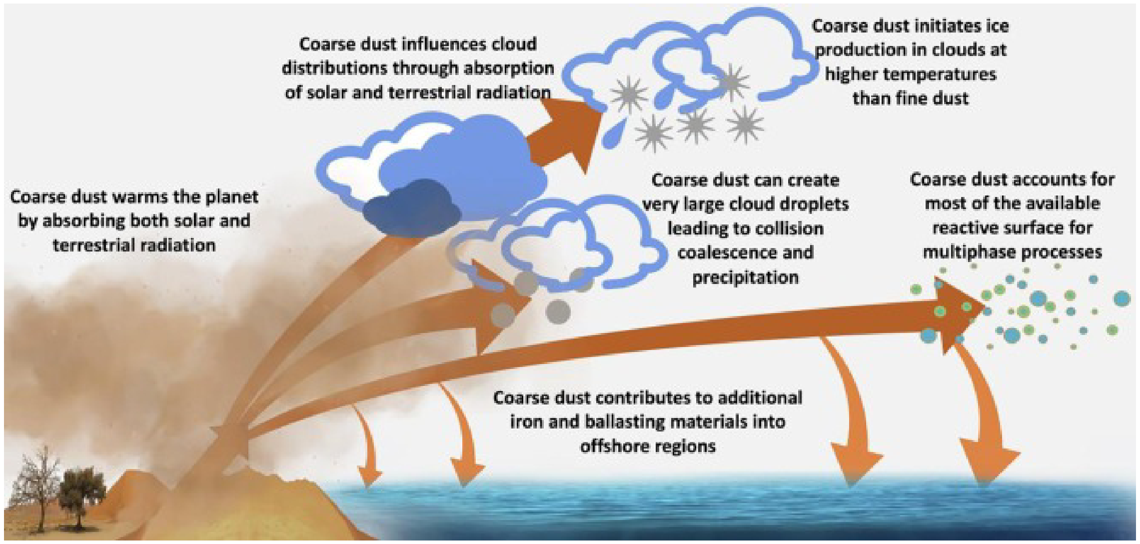

Fig. 3: Coarse dust (and super-coarse dust) impacts several aspects of the Earth system, including radiation, clouds, precipitation, atmospheric chemistry, and biogeochemistry Source: (Adebiyi et al., 2023)

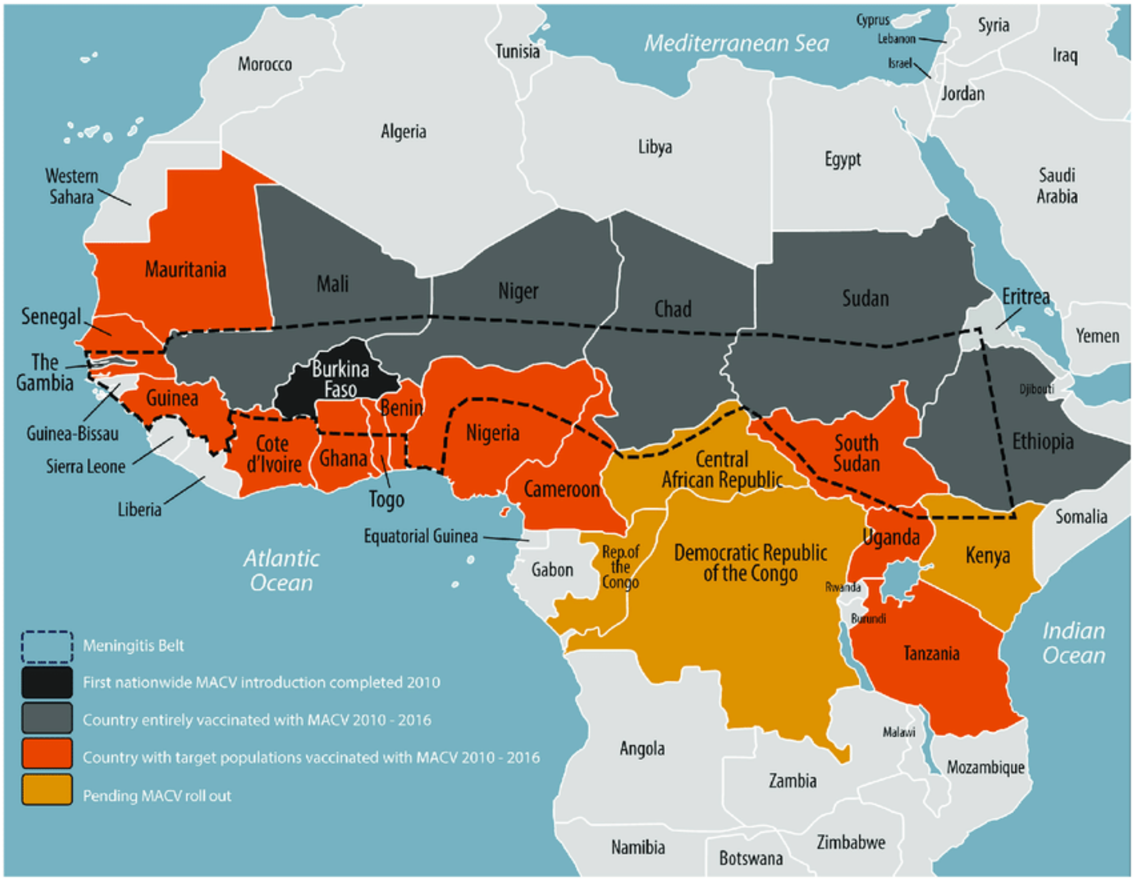

Fig. 4: The meningitis belt of sub-Saharan Africa and meningococcal serogroup A conjugate vaccine (MACV) rollout, 2010-2016. Source: (Diallo et al., 2017)

Fig. 5 Saharan dust makes the trans-Atlantic journey from the Sahara desert to the Amazon rainforest. Credit: NASA's Goddard Space Flight Centre.

Source: http://www.sci-news.com/othersciences/geophysics/science-phosphorus-rich-dust-sahara-desert-amazon-soils-02533.html (accessed 30.05.2022)

Table 1: Possible explanations for the impact of desert dust on meningitis epidemics in West Africa.

SN	**Hypothesis**	**Reference**
1	Increase in invasion rate (i.e. a shift from carrier to infected status) due to high dust loads and persistent low humidity damaging immune defences in the mouth and easing bacterial invasion	(WHO, 2021)
2	Higher transmission levels due to changes in living habits, such as the proximity of individuals taking refuge from dusty winds	(WHO, 2021)
3	Co-occurrence of viral respiratory infections weakening the immune system and easing transmission and invasion by bacteria	(Mueller et al., 2008)
4	*Neisseria* bacteria, responsible for meningitis, require iron-rich dust to grow and become virulent	(Noinaj et al., 2012)

Source: Updated after (Middleton, 2017)