Airborne soil-derived dust hazards in aviation

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Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-23-0311.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

ABSTRACT: Airborne mineral dust poses a safety challenge for aviation. Several fatal accidents have happened in dust-laden air due to reduced visibility, strong gusty winds, and wind shear. Dust-induced icing also contributed at least to two fatal accidents. Furthermore, atmospheric dust has long- and short-term effects on aircraft operating condition due to corrosion and abrasion on the aircraft surfaces, and molten ingress deterioration of engine hot section components. The combined impact can increase operating and maintenance costs, and increase the overall cost of ownership. While the scientific community has started preparing and providing products based on atmospheric dust modeling and observation, there are still important data and information gaps in the fundamental science. These include (i) insufficient data which could be used to better understand the effects of dust on aircraft as well as on ground systems and operations (e.g., four-dimensional information of dust mineralogy, cost-benefit analysis of the impact of dust on aviation along flight routes), (ii) the identification of airborne dust monitoring and modeling products and services that could enable the flow of relevant information in commercial aviation and in decision-making workflows, and (iii) the underdeveloped, unclear, or absent role of dust hazards in regulations and operational procedures as well as in the training, skillset, and knowledge base of pilots. This review is aimed at both academic and aviation stakeholders, and presents the current state-of-the-art knowledge at the intersection of dust hazards, aviation safety, and impacts on flight operations and aircraft maintenance.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0311.1.

SIGNIFICANCE STATEMENT: Several fatal air traffic accidents and incidents have been clearly attributed to the presence of atmospheric dust. Furthermore, dust has long- and short-term effects on aircraft functioning due to corrosive, abrasive, and melting effects on the aircraft skin and engines, which represents a substantial cost of ownership risk for aviation. In the present article, we aim to bridge aviation stakeholders and research communities, synchronizing and facilitating their efforts to address emerging issues related to the intersection of dust hazards, aviation safety, and costs of operations and maintenance. We fill this gap by reviewing and highlighting the impacts of dust on aviation, introducing and discussing the added value of tailored products, and publishing recommendations for both data providers and end-users.

CAPSULE: Current tools and data that track and predict airborne mineral dust transport can help the aviation community enhance flight safety and reduce its impact on flight operations and maintenance costs.

1. Introduction

Natural, political, regulatory, societal, and economic factors can strongly affect the aviation industry. Major air traffic disruptions associated with geopolitical tensions, environmental hazards, or health-related issues can cause significant economic losses to the aviation sector (Alexander 2013; EUROCONTROL 2022). While some of these problems cannot be avoided, it is possible to minimize the risk of others by exploiting advanced scientific knowledge based on monitoring and forecasting.

High atmospheric aerosol and particulate loadings may pose an immediate hazard to aviation that can impact the safety of flights (e.g., Casadevall 1994). Several air traffic incidents were caused by volcanic ash, causing damage to the aircraft and in some cases loss of engine thrust (e.g., Guffanti et al. 2010; Clarkson et al. 2016). Severe incidents were also caused by sea salt aerosols (Reid et al. 2007; Tighe 2015; Boucher and Rémy 2016), fire-emitted aerosols (Knežević 2020), and airborne mineral dust.

Dust is one of the most abundant aerosols at the global scale but possibilities in managing its impacts are not well recognized in the aviation community. However, there are also a number of air traffic accidents and incidents clearly attributed to the presence of mineral sand and dust emitted from hyper-arid, arid, and semi-arid regions (Middleton 2017; Nickovic et al. 2021). An analysis of historic air traffic incidents in Australia revealed a decreasing trend of sand- and dust-related incidents from 1969 to 2010, which was explained by technological improvements (Baddock et al. 2013). Nowadays, aviation safety in dust-laden air is mainly degraded by reduced visibility, strong gusty winds, and wind shear (e.g., Middleton et al. 2019; Cuevas et al. 2021; Monteiro et al. 2022). For example, 14 people were killed in an aircraft accident in Tunisia in May 2002 during a dust storm with severe meteorological and low visibility conditions (Tunisia Republic 2004). Similar accidents happened in India in May 2011 (with 10 fatalities) and in Sudan in August 2012 (31 fatalities, Middleton 2017). Dust-induced icing also contributed to two fatal accidents in 2009 and in 2014 (Nickovic et al. 2021). Apart from these accidents in civil aviation, dust storms also had severe effects on air ambulances in Australia (Holyoak et al. 2011) and military operations in the Middle East (Henderson 2014). In order to avoid dust-related accidents, aircraft are usually grounded during severe dust storms or diverted to other locations. Flight cancellations, delays, or reroutings, however, cause a significant economic loss for the aviation industry (Williams and Young 1999; Tozer and Leys 2013; Cuevas et al. 2021; Monteiro et al. 2022) and, of course, an inconvenience for passengers.

Mineral sand and dust is abrasive and can mechanically damage different parts of the aircraft (Smialek 1991; Brun et al. 2011). When coupled with long-term exposure, dust can cause an increase in the cost of maintenance due to the deterioration in engine performance and in-service life, through premature component failure (Wood et al. 2017; Bojdo et al. 2020). Corrosive and abrasive effects as well as melting in turbines reduce fuel efficiency and increase maintenance, repair, and overhaul (MRO) costs, presenting non-negligible economic risks for airline operators, aircraft lease companies, and engine manufacturers.

The primary distinction between airborne mineral sand and dust is based on the particle size, with sand being larger than dust (larger than approximately 60 μm, see Adebiyi et al. 2023). However, since we will not discuss any size-dependent impact of these particles on aviation, we will not distinguish between sand and dust particles (SDP) in this manuscript and hence SDP will refer to all particles emitted from soil surfaces. Aircraft damage depends on the chemical and physical characteristics of SDP (Wood et al. 2017; Bojdo et al. 2020) and on time exposure (Clarkson et al. 2016). Particles composed of silicates, for example, are harder than metal alloys used in engine components and cause erosion to the fan, compressor, and combustor sections

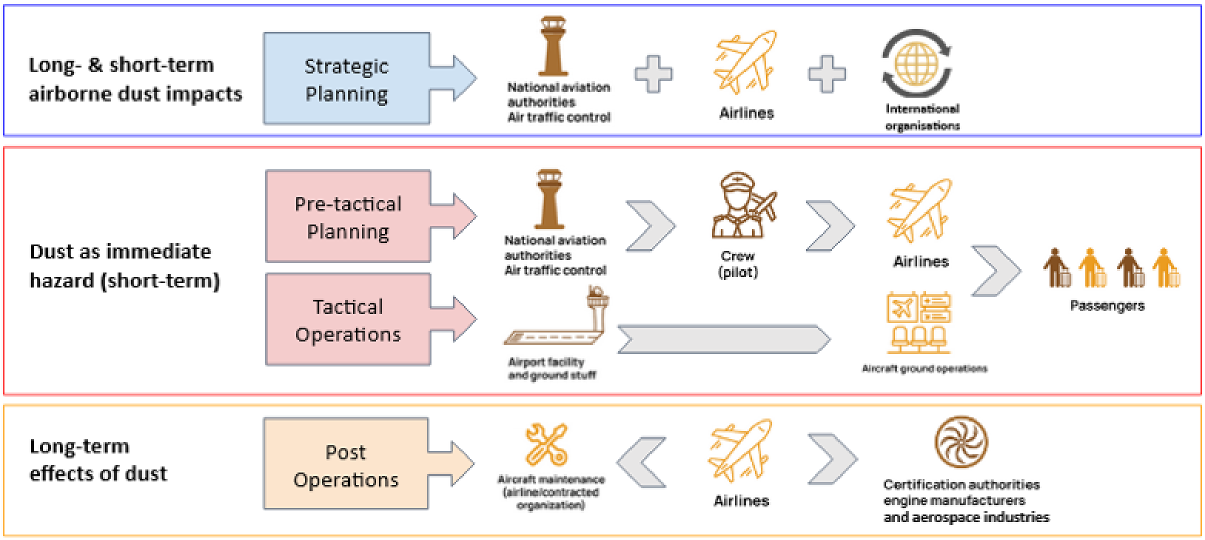

FIG. 1. Impacts of dust on different air traffic management phases and affected stakeholders.

of gas-turbine engines. Carbonate and sulfate minerals but also many aluminosilicate minerals can melt in the hot sections of current gas-turbine engines, blocking cooling holes and damaging ceramic coatings, which leads to rapid deterioration of the engine components (Wood et al. 2017). These mechanisms currently cause most problems with commercial aviation in dusty regions.

The impacts of dust hazards on civil aviation are diverse but they can broadly be split into the different air traffic management phases (see Fig. 1): (i) strategic planning, which consists of forecasting and capacity planning, route optimization, and airspace design, (ii) pre-tactical planning (i.e., 24 hours before the departure) and tactical operations, which are affected by the immediate hazard (i.e., if an intense sand and dust storm (SDS) approaches an airport and limits airport operations), and (iii) post-operation, which is essential for stakeholders who undertake MRO, to deal with long-term effects of dust exposure on aircraft and engine performance (e.g., Ryder et al. 2024).

The national aviation authorities are in charge of prescribing special conditions for aerodromes that require specific safety measures, while the meteorological conditions (e.g., visibility, wind speed and direction) for each airport are published as observed by Meteorological Watch Offices (MWO) or forecasted by the aerodrome meteorological office. To reduce the risk for aviation, airports and air traffic control (ATC) typically limit or suspend operational services during intense SDS, reduced visibility, and high wind speed. Service limitations can range from lowering the rate of operations (e.g., number of landings or take-offs) to total airport closure if the conditions caused by SDS are deemed unsafe (e.g., visibility is below a safe threshold). This has implications for air-side operations, which include aircraft landing/take-off and navigation, airport traffic management, runway management, and ground handling safety (ICAO 1986). Flights can be therefore delayed, re-routed, or canceled disrupting the airport and airline operations, and passenger travel. Passenger operations (e.g., check-in, baggage handling, boarding) and landside operations (e.g., passenger pickup and drop-off curb areas of the airport, parking facilities, and other forms of transportation) can be affected as well.

The operator (e.g., an airline) is responsible for the maintenance of the aircraft and its engines (ICAO 2010, Annex 6, Chapter 8). However, since most engines are now sold with maintenance services (e.g., "power-by-the-hour"), the engine original equipment manufacturers (OEM) cover all repair and overhaul liabilities if an engine is damaged or suffers irrecoverable loss of performance through dust exposure. Current engine and airframe certification regulations established by the certification authorities (such as the European Union Aviation Safety Agency – EASA, the Federal Aviation Administration – FAA, or Transport Canada Civil Aviation – TCCA) do not define a dust concentration limit, or duration of exposure, above which engines and the airframe would need to demonstrate acceptable operation. This implicitly means that safe flight and landing of the aircraft must be ensured under all conditions (any naturally occurring concentration and likely operational exposure levels, see EASA CS-E 540(b) and 580 regulations, EASA 2020).

The aircraft and engine industries are investigating the impacts of dust on aircraft maintenance in order to reduce MRO and operating costs. In parallel, the scientific community prepares and provides dust-related products, which are tailored to the needs of the aviation end-users (Amiridis et al. 2013; Hirtl et al. 2020; Papagiannopoulos et al. 2020; Votsis et al. 2020; Ryder et al. 2024). The objective of the present review is to bridge the aeronautical and atmospheric research communities, synchronizing and facilitating their efforts to address emerging issues related to dust impacts on aviation safety, expecting that more aviation-oriented products will be available in the future. Such collaboration should enable more accurate assessments of the benefits of using improved dust-related information.

A. Runway and Taxiway: Dust contamination and reduced visibility

B. Engines: Engine blades: abrasion and corrosion; Melting of dust; Blockage of cooling holes

C. Passengers & personnel: Potential health effects

D. Wheel assemblies: Abrasion and corrosion

E. Pitot tubes and static port: Abrasion and blockage (by dust and dust-induced ice particles)

F. Aircraft skin: Abrasion, corrosion and electrostatic charging

G. Windscreens: Abrasion

H. Nose cone: Abrasion and corrosion

FIG. 2. Aircraft- and some airport-related impacts of mineral dust.

2. Impact of dust on aviation

Airborne dust is a geographically widespread phenomenon (UNEP, WMO, UNCCD 2016). On a global scale, the largest dust sources are located in northern Africa and the Middle East, in Central and Eastern Asia, central Australia, the west coasts of south Africa and South America, and south-west North America (Ginoux et al. 2012). Dust events in other regions, including higher latitudes, usually caused by emissions from degraded lands and other exposed surfaces, are recently also receiving increased attention because of the growing impact of climate change (Vukovic Vimic 2021; Meinander et al. 2022; UNCCD 2022). While the impacts of dust on aviation are largest close to the major dust source regions, where SDS are most severe, significant problems can also occur far away due to long-range transport (i.e., dust can travel several thousand kilometers) and indirect effects of dust. A detailed understanding of the impact of dust on aviation is important to minimize associated safety risks as well as economic loss. This section reviews negative airborne dust impacts affecting different phases of flight operations. Figure 2 summarizes most of these impacts on aircraft and runways for readers who are not familiar with the aviation-specific nomenclature.

a. Airport operations

SDS can significantly affect the activities at an airport. During very intense SDS with high wind speeds and significantly reduced visibility, as a preventive measure, passengers and personnel need to stay inside the buildings. This helps prevent people from being injured by flying debris and minimizes potential health effects from dust exposure (WHO 2021). All vulnerable parts of the grounded aircraft shall be covered to avoid intrusion and possible mechanical damage due to airborne aerosols. This includes nose cones, windscreens, wheel assemblies, engine cowlings, and pressure instruments that provide airspeed and altitude information (e.g., Pitot tubes and static ports), which need to be protected against possible blockage due to dust sedimentation (e.g., Jackson 2015; EASA 2021) and subsequently incorrect measurements (e.g., AAIB 2022). Water-soluble minerals, contained in the dust, can cause metal corrosion to the airframe. To prevent this, dust deposits should be removed within an adequate time span (i.e., usually before the next flight). Since the contamination of the runway can adversely affect take-off and landing performance, runway cleaning might be required after the event (ICAO 2002a, 2018a).

Reduced visibility is the major and most common problem of in-flight and ground traffic in dusty conditions, which typically requires reactive measures. During extreme SDS, visibility can be reduced to near-zero which makes any movement during the event difficult, dangerous, or even impossible (see Fig. 3). Visibility depends on the humidity (e.g., Hänel and Zankl 1979; Zieger et al. 2013) and concentration of particles suspended in the air as well as aerosol optical properties (e.g., Waggoner and Charlson 1977). The literature shows large uncertainties on the estimation of the effects of aerosols on visibility in desert regions in North America (Chepil and Woodruff 1957; Patterson et al. 1976), Australia (Baddock et al. 2014), Asia (Shao and Wang 2003; Wang et al. 2008), and West Africa (d'Almeida 1986; Ben Mohamed et al. 1992; Camino et al. 2015). These large uncertainties can partly be explained by using particulate matter of different size as proxy for dust and by different distances to the dust source region (optical obfuscation properties vary with size, dust size population decreases with the distance from the source because large particles drop out and remaining particles are finer sized far away from the source region).

If operations in low visibility conditions are permitted at an airport, the air traffic, meteorological, and aeronautical information services provide relevant information[1]. Well-defined and articulated procedures for operations in reduced visibility situations facilitate decision-making processes in aerodrome traffic management (ECAC 1988; ICAO 2013, 2016a), including surface movement guidance and control (ICAO 1986, 2004). Four visibility conditions regulate ground activities (see Fig. 3). Visibility condition 2 occurs when ATC is unable to exercise control over air traffic on the basis of visual surveillance, and depends on the airport conditions and area it covers. This and visibility conditions 3 and 4 (associated with visibilities <400 m) lead to reduced airport capacity

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[1] These services, as a regulatory requirement, broadcast information to all airspace users, in all weather and operational conditions

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

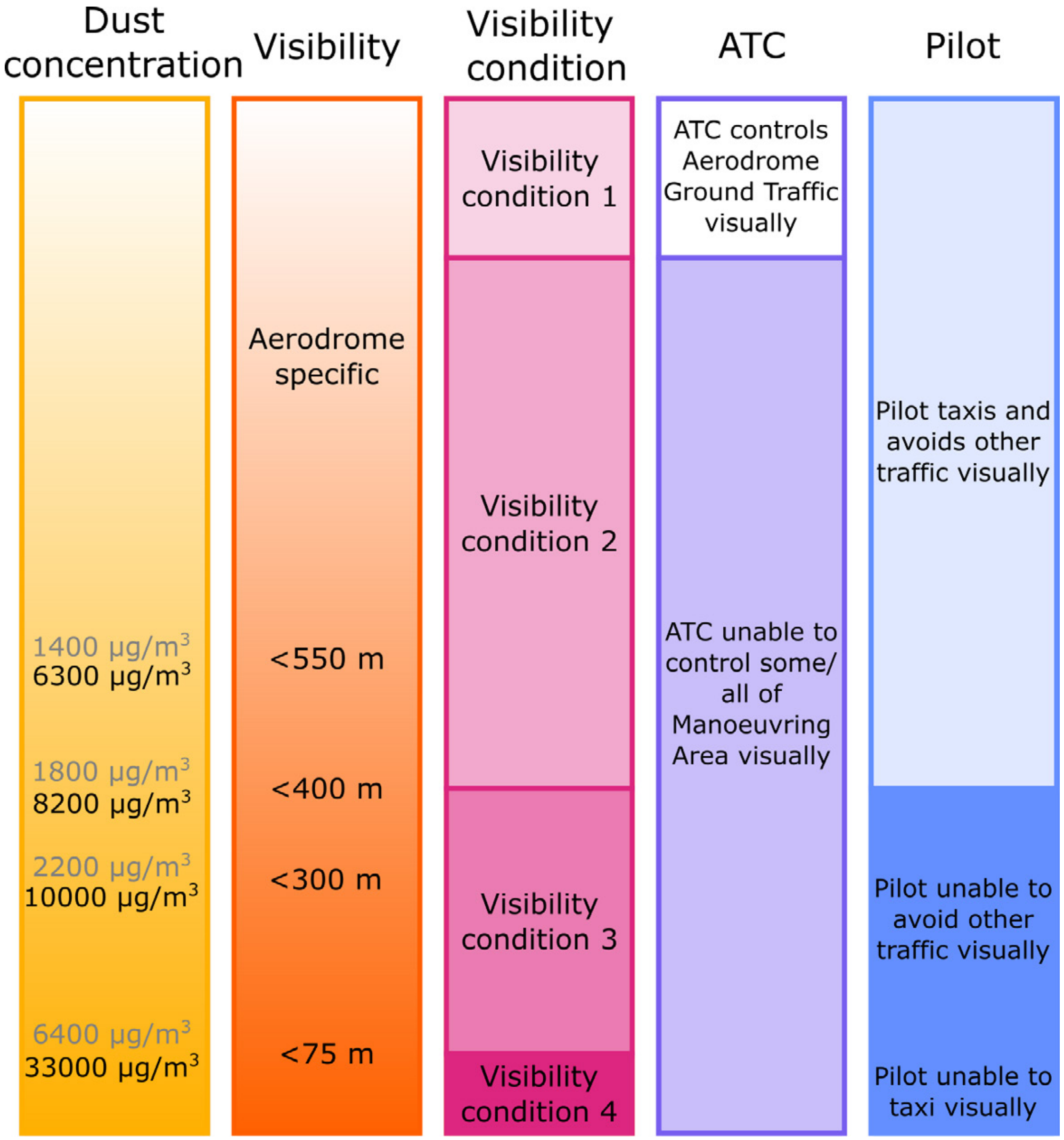

FIG. 3. Relationships between dust concentration (left gold bar; gray numbers after d'Almeida (1986) and black numbers after Shao and Wang (2003), differences are described in Camino et al. (2015)), visibility (orange), visibility conditions (magenta), situations for ATC (indigo), and pilot actions (ultramarine). Modified after ICAO (2016a).

and can increase workload for air traffic management (ATM) and ATC. Economic and tactical impacts of disturbances in airport operations are caused by delayed departures and arrivals, flight

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0311.1.

rerouting, flight cancellations, and even airport closures (e.g., Al-Hemoud et al. 2017; Alkheder and Alkandari 2020; Monteiro et al. 2022).

b. Impact during take-off and landing and at low flight levels

On dry dusty surfaces, helicopters, tiltrotor aircraft, and other vectored thrust aircraft operating near the ground can generate dust concentration levels of several 100 mg/m^3, which is usually referred to as brownout conditions. Several helicopter accidents were caused by brownout conditions, which obscure the pilot's vision of the terrain and are therefore a significant safety threat, primarily affecting military operations in desert environments (see, e.g., Wadcock et al. 2008; Gillies et al. 2010, for more detailed information). The detailed discussion of this phenomenon, however, is outside the main consideration of this paper.

In the lower atmosphere, dust can also reach very high concentrations ($> 40000\ \mu$g/m^3; ADEQ 2012) up to 2 to 3 km above ground during major SDS (e.g., Cuevas et al. 2021; Monteiro et al. 2022), affecting the critical phases of flights, such as take-off, climb, descent, holding patterns, and landing (Ryder et al. 2024).

During these flight phases, SDP rubbing against the aircraft skin can amplify the process of charging it (Matsusaka et al. 2010). After several seconds under continuous impacts, the aircraft reaches an electrostatic equilibrium (Pechacek et al. 1985; Lekas 2019). The corresponding charge distribution creates an electrostatic field at its vicinity, which can induce noise in radio communications of the aircraft (Starr 1941; Tanner and Nanevicz 1964; Alozie et al. 2023). This electrostatic charging also represents a potential hazard for ground personnel during refueling or loading operations (Gigliotti 2012; Lee 2019). In addition, it can be a problem for onboard electronic devices that are not well protected from electromagnetic interference (Lekas 2019).

The long-term exposure to dust during flight can abrade aircraft surfaces including windscreens, landing light screens, propeller and jet engine blades, as well as avionics (e.g., Smialek 1991; Brun et al. 2011). Erosion of external surfaces increases total drag and results in higher thrust settings and fuel consumption (leading to economic and environmental impacts) as well as reduced endurance and range of the aircraft. Surface damage of an engine (including abrasion and increases in compressor blade running clearances) can lead to gas flow deterioration and a gradual loss of the engines' performance and efficiency (e.g., Smeltzer et al. 1970; Hamed et al. 2006; Bojdo and Filippone 2014, 2019; Clarkson and Simpson 2017; Szczepankowski et al. 2017). Increased maintenance intervals and economic costs can result from aircraft flying through moderately dusty regions on a regular basis. This has become a more prominent issue in recent years due to (i) the rise in air traffic in dusty regions such as the Middle East and (ii) the use of engines which are less tolerant to atmospheric aerosols because of increasing operating temperatures (Wood et al. 2017). Ryder et al. (2024) show that this can be exacerbated when hold patterns coincide with the altitude of the local elevated dust plume but could be mitigated by nighttime take-offs and landings.

Volcanic ash particles have been considered almost exclusively as a severe hazard because of melting in jet engines and depositing on the blades and inner parts. However, the continuous increase of turbine operating temperatures also raises the danger of dust melting (Wood et al. 2017) despite having up to a few hundred Kelvin higher melting points than volcanic ash. Furthermore, dust melting inside engines can lead to blockage of cooling holes (Cardwell et al. 2010). Therefore, dust exposure leads to a gradual reduction in engine efficiency and durability of certain components, mainly in the hot section of the engine.

The amount of melted dust deposit that builds up is a function of dust concentration, exposure time, engine thrust, and mineralogical composition (Clarkson and Simpson 2017; Wood et al. 2017; Bojdo and Filippone 2019). Mineralogical composition of transported dust depends on the soil characteristics at dust sources (e.g., Nickovic et al. 2012; Gonçalves Ageitos et al. 2023). Mineralogical characteristics of transported SDP are also important to predict because the combination of different molten minerals can exhibit different chemical properties and lead to thermal corrosion of engine components or electronic devices (Elms et al. 2021).

The relationship between the degree of engine damage and dust concentration and exposure duration has been established for some time, essentially through observations from engines in aircraft operating in dusty environments or from controlled engine dust tests (Dunn 1991a,b; Baran and Dunn 1996a,b). A more recent investigation of the influence of particulate concentration and exposure time on engine damage was performed by Clarkson et al. (2016) and Clarkson and Simpson (2017), who established a duration of exposure versus atmospheric concentration (DEvAC) chart of volcanic ash and mineral dust.

Figure 4 illustrates an updated DEvAC chart for specifically mineral dust exposures, which is based on data from in-service exposure events and controlled engine tests using dusts. The outcome

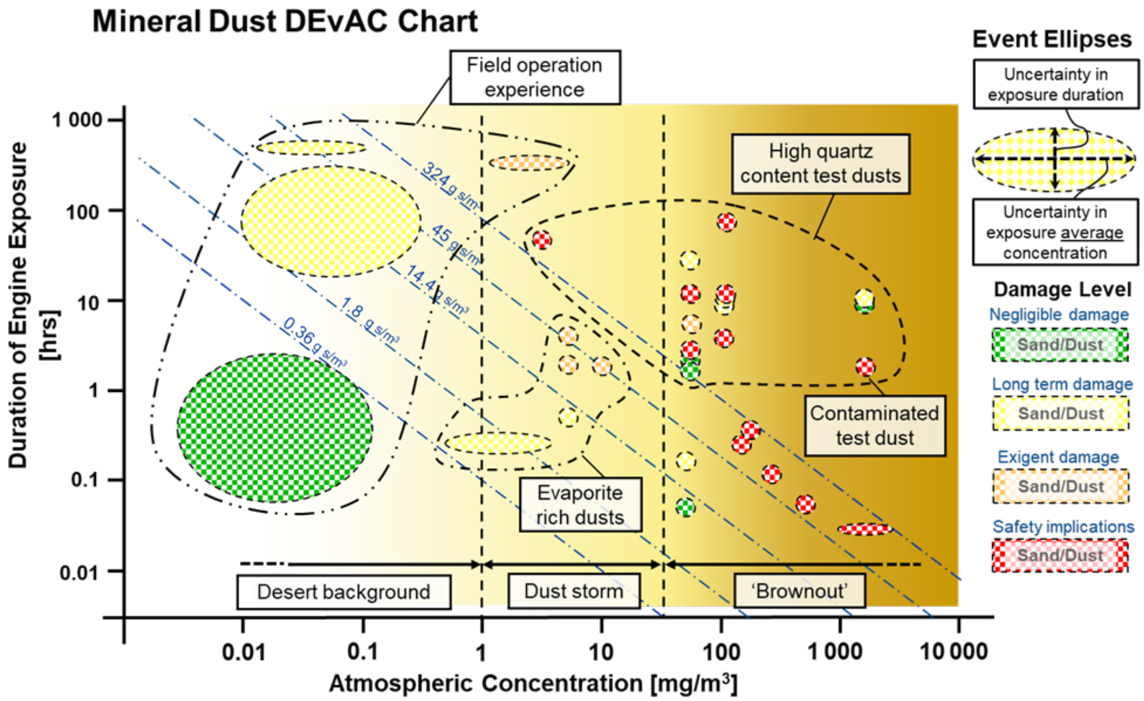

Fig. 4. Mineral dust Duration of Exposure versus Atmospheric Concentration (DEvAC) chart. The background colored shadings refers to dust concentrations. The uncertainty in the mean dust concentration and the duration of an encounter are represented by the horizontal and vertical axes of the event ellipses, respectively. Circular event points generally represent controlled tests. The diagonal lines indicate exposure doses, the product of the concentration and exposure duration. Source: Modified after Clarkson et al. (2016).

of each exposure event was categorized into (i) negligible and essentially undetectable damage, (ii) long-term economic damage, in terms of reduced efficiency or reduced service intervals, but without any immediate maintenance activity, (iii) exigent damage, which has manageable safety implications and immediate inspection and appropriate maintenance procedures are required, and (iv) a significant deterioration in safety margins.

A distinct pattern in level of damage relative to mineral dust concentration and exposure duration reveals a greater level of damage at greater exposure doses. However, some of the detailed mechanisms driving damage, and how it accumulates (the damage–dose relationship) are not entirely linear. At very high dust concentrations, a lower exposure dose is required to produce safety concerns than the exposure dose required at much lower concentrations. The much longer exposure durations needed to achieve a given dose means that self-repair, or damage removal mechanisms can come into play. But such effects can only occur when the damage has a self-repair capability (e.g., hot section deposition, which experiences shedding with time and reduces damage). Further, the picture becomes more complex because of other factors such as variations in engine design, the age of technology it contains, and mode of operation, but also the nature of the particulates.

The effect of different engine designs and operating temperature reveals a relative scatter in damage level outcomes as shown for quartz dust test samples (collections of points in the top right-hand quadrant of Fig. 4). In general, higher temperatures were found to accelerate damage rates, especially in the hot sections of the engines. The point labeled "Contaminated test dust" shows the detrimental impact of (inadvertent) inclusion of other minerals which melt at lower temperatures to quartz. The level of damage is accelerated, relative to the two repeat tests vertically above, conducted on the same engine type but with pure quartz dust. Also note, the engine type in question included an inlet particle protection system, hence its greater tolerance to high exposure doses.

c. Impact during aircraft cruising at high flight levels

While volcanic ash is a severe risk at cruise levels (usually at an altitude between 10 and 12 km), the main threat from dust at these altitudes is associated with icing in and around convective weather systems. SDP can nucleate ice crystals in deep convective anvil cirrus. Over the last two decades, commercial airplanes have reported more than 150 cases of engine power-losses and damage caused by cloud ice crystals (Haggerty et al. 2019). Furthermore, icing of instruments and sensors can result in false readings (e.g., barometric altimeters, airspeed and vertical speed indicators). Pitot tubes are particularly sensitive to icing which can cause obstruction and a bad airspeed indication, confuse pilots, and therefore degrade the flight safety.

Dust aerosols at small concentrations in the upper troposphere can initiate efficient ice nucleation (Cziczo et al. 2013; Froyd et al. 2022). Aircraft on-board weather radars often fail to observe ice crystals in anvils of convective clouds and so increase the risks due to icing (Haggerty et al. 2019).

The role of dust on ice formation along the routes of two flights with catastrophic outcomes has been studied by Nickovic et al. (2021). Official investigation reports identified icing along the routes crossing the periphery of the convective system as the cause of both accidents (BEA 2004;

CEAIAC 2016). Observations indicated the presence of high-altitude dust lifted from African sources by convection to the upper troposphere (Nickovic et al. 2021).

3. Dust products for the aviation sector

The development of aeronautical products and services requires continuous Earth observations from satellite, ground-based systems, as well as atmospheric chemical transport models that are capable of predicting the strong dynamics of dust uplift and transport, and the consequent reduction of visibility.

Global hazard monitoring platforms and early warning systems are fundamental for anticipating severe hazards and fostering better decision-making (Hirtl et al. 2020; Papagiannopoulos et al. 2020; Brenot et al. 2021; Amiridis et al. 2023). Due to the absence of clear guidance on the relative importance of the physico-chemical mineral dust properties (i.e., size spectra and mineralogy), the development of tailored products and services for the aeronautical sector is at present in its initial stages. To address the emerging needs of the aeronautical service to manage the risk or mitigate the impacts of SDS, the atmospheric research community is working on the identification of gaps in current monitoring infrastructures (Mona et al. 2023) and modeling capabilities (Benedetti et al. 2018; Vukovic Vimic et al. 2021) to provide better products that ultimately can contribute to improving air traffic management and safety.

In order to minimize the impacts of the hazards associated with dust at airports, aeronautical meteorological services provide information on dust conditions associated with visibility obscuration. Depending on the intensity of the phenomenon, forecasters may include this information in regular reports and issue different types of warnings. If the prevailing visibility is equal to or lower than 5000 m, the type of obscuration must be included in the Terminal Aerodrome Forecast – TAF (ICAO 2018b; WMO 2019). In the same way but with the aim of providing information for a specific area, forecasters include information about visibility and weather phenomena, i.e., AIRman's METeorological Information (AIRMET), General Aviation METeorological forecast (GAMET), and charts for low-level flights (ICAO 2018b). In case of heavy SDS, MWOs must issue Significant Weather Information (SIGMET) and the meteorological office designated by the meteorological authority concerned will issue aerodrome warnings (ICAO 2018b).

Final flight planning and decisions rely on actual, rather than forecast, weather at the time of departure or approach and landing. A Meteorological Aerodrome Report (METAR, WMO 2022) is issued for airports with commercial flight operations and contains key weather observational conditions, including visibility (and its cause, such as dust), and may, if warranted, include a forecast component in the form of a trend for the two hours following the time of the observation. Often the forecasts and actual weather services are combined in a VOLMET ("vol météo": meteorological information for aircraft in flight) for a region to provide key information for en route aircraft in that region. In many cases, recorded meteorological information is broadcast automatically via an Automatic Terminal Information Service (ATIS) and is updated every 30 minutes. For airports with controlled traffic, it is mandatory for the pilots to access and follow the information.

METARs, TAFs, world area forecast systems (WAFS), and SIGMETs are produced and made available for aviation users, to serve terminal area and en route flight operations. Some of these products cover an aerodrome and its vicinity only (as METAR, TAF) or consider a flight information region (as SIGMET). Further tools used consist of weather radar systems that are installed inside the aircraft's nose cone and display storm-related information in the cockpit, as well as satellite weather information services paired to the aircraft's avionics. However, such information does not record dust-related parameters.

While ground-based in-situ observations provide valuable information on near-surface aerosol concentration, airborne aerosols can also be detected with aircraft in-situ measurements (Weinzierl et al. 2012; Petzold et al. 2015; Ryder et al. 2018), ground-based regional/global networks/research infrastructures (e.g., Mona et al. 2012; Haefele et al. 2016; Giles et al. 2019; Papagiannopoulos et al. 2020; Laj et al. 2024), or satellite-based remote sensing products (e.g., Amiridis et al. 2013; Burton et al. 2013; Sayer et al. 2014; Capelle et al. 2018; Callewaert et al. 2019; Clarisse et al. 2019; Vandenbussche et al. 2020). Qualitative (as in the case of aerosol-type products from satellites) and quantitative (e.g., dust surface concentration or aerosol layer height) observational dust products allow for monitoring an SDS (in terms of extension, intensity, and dynamics) but also for detecting aerosol layers and types, which are hazardous for aviation (Papagiannopoulos et al. 2020; Brenot et al. 2021). An extended review of the current dust monitoring capabilities, suitable available products for the aeronautical sector, and identified gaps are discussed in Mona et al. (2023). Furthermore, in the coming decades, international satellite agencies are planning new missions, such as the Meteosat Third Generation (MTG) program or Plankton, Aerosol, Cloud, ocean Ecosystem (PACE), that promise significant advancements in the observation of atmospheric dust. These improvements will enhance the accuracy and number of dust-related satellite observations.

Numerical weather and climate models, with embedded prognostic dust-related variables, are valuable for forecasting SDS evolution in space and time as well as for assessing their potential impacts in the aeronautical sector. Coupled dust-atmospheric numerical models provide four-dimensional (4D) estimations of the dust concentration, including size distribution, emission and deposition rates. Moreover, the research community is conducting large efforts to incorporate information about dust composition in numerical models (Nickovic et al. 2012; Remy 2021; Gonçalves Ageitos et al. 2023). Model outputs can be used to produce tailored products, e.g., exposure to airborne dust over a particular route (can be used for long-term planning) (Votsis et al. 2020; Ryder et al. 2024) or a risk assessment related to the melting and icing impact due to the presence of dust (important for day-to-day operations) at regional and global scales. Models' performance is highly sensitive to the information on soil characteristics and conditions (mapping of dust sources) and to the representation of surface winds. While global and synoptic-scale dust events are well-monitored and modeled, our understanding and prediction of smaller-scale events such as haboobs remain limited (IPCC 2021, 2022; Marsham and Ryder 2021; Vukovic Vimic et al. 2021). SDS which originate from severe convective activity (as haboobs) or highly variable surface wind gusts of other origin, require implementation of high-resolution forecasts (several kilometers resolution; Vukovic et al. 2014; Rooney 2017; Vukovic Vimic et al. 2021), which is common in operational regional weather forecasts.

While modeling products are not error-free (e.g., Xian et al. 2019; Gliß et al. 2021), dust reanalyses are the most accurate source of information for long-term analysis that allow studying dust processes in remote areas, with insufficient observational data. A reanalysis product is a consistent and harmonized long-term modeling product of past periods which provides spatially and temporally complete distributions of dust transport at regional and global scales (e.g., Escribano et al. 2022). Reanalyses are obtained by a data assimilation method that combines available observational data and model information. Reanalyses (e.g., Lynch et al. 2016; Buchard et al. 2017; Yumimoto et al. 2017; Inness et al. 2019; Di Tomaso et al. 2022) are the basis for the development of improved climatologically representative impact assessment studies, meaning that they aim to address "objective environmental threats to operations" (e.g., ESCAP/APDIM 2021). Modeling products for climatological assessment (i.e., dust reanalysis) or short-term planning (i.e., forecast) can support cost optimization, planning, operations, and investment risk indicators for airports and route investments.

Several models are implemented worldwide to provide global and regional dust forecasts (Benedetti et al. 2018; Xian et al. 2019; Gliß et al. 2021). To increase the reliability of the operational dust forecast (i.e., on short-term scales) and to assess the range of possible outcomes, use of ensemble is an option. Ensemble forecast products can provide probability of the hazard conditions particularly in the case of extreme events (e.g., Cuevas et al. 2021; Monteiro et al. 2022). The model ensemble approach is common in weather forecast meteorology and climate studies and is also used in air quality (e.g., Copernicus Atmospheric Monitoring System, CAMS) and atmospheric composition (e.g., International Cooperative for Aerosol Prediction, ICAP). The purpose of ensemble forecasts is to comprehend the impact of the most significant uncertainties (represented by perturbed inputs or using different parameterizations) on the outcome of the forecast. Knowledge of the most probable conditions and the possibility of the high-risk conditions can be of great utility to users in aviation since it can inform safety risk assessments, for example.

The generation of multi-model ensemble products is one of the core activities of the World Meteorological Organization (WMO) research programme, the Sand and Dust Storm Warning Advisory and Assessment System[2] (SDS-WAS, Werner et al. 2023). Currently, the SDS-WAS includes multi-model intercomparisons at regional and global scales including some of the global models participating in the ICAP model ensemble. Another obstacle for improvements of aeronautical products and their understanding from the wider community is the lack of specific definitions and standards for airborne dust-related parameters (definition of variables related to surface concentration, dust concentration on different levels, deposition rates, etc). This needs the involvement of aviation stakeholders, providers, scientists, and the international agencies (including ICAO and WMO).

Despite operational dust forecasts being produced by several forecasting centers, they are usually not distributed as MET (meteorological information for aviation) products, although they are crucial for the aviation sector. Further, the atmospheric research community is engaged to provide some

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[2] https://community.wmo.int/activity-areas/gaw-sand-and-dust-storm-warning-advisory-and-assessment-system-sds-was

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

new useful products for the aeronautical sector such as indicators of icing due to dust or melting (Marinou et al. 2019; Nickovic et al. 2021). These initial efforts of the atmospheric community and the provision of aviation-related products would benefit from better developed interdisciplinary collaboration.

4. Recommendations and discussion

The previous sections demonstrate that more information about the interaction of mineral dust with commercial aviation is needed to address the growing short- and long-term safety and economic concerns. At present, there is a great need for a clear definition of dust-related hazards and the associated impacts on aviation. While products tailored to the above purpose could be generated, there are no standards originating from the aviation sector; thus, such products will not be integrated well into regulation and operations.

Reports of current or forecasted weather affecting airports or flight routes (cf. Section 3), provide dust-related warnings, indirectly (through visibility) or directly (e.g., widespread dust, sand, dust storm, sandstorm). This is not enough, however, for a highly specialized and regulated sector such as commercial aviation: it is difficult to infer or quantify from such weather reports concrete short- and long-term impacts for specific aircraft and engine systems or flight operations. An approach to further develop the link between dust-related products and aviation should be based on three lines of action, keeping in mind that human factors are as crucial as technical information:

(a) Address the insufficient data (observed or modeled) to better understand the interactions and negative impacts between mineral dust and the various aircraft and ground systems in commercial aviation.

Such data should provide understanding of the exposure of aircraft and engines in four dimensions: geographies (flight routes), pressure altitudes (flight levels), times (seasons), and chemical composition. This would be used to enhance engine condition monitoring. Ground or en route observations can only partially fulfill this objective. Current operational forecasting systems (e.g., Xian et al. 2019; Cvetkovic et al. 2022; Kim et al. 2023) and advanced atmospheric reanalyses (e.g., Inness et al. 2019; Di Tomaso et al. 2022) can provide spatial and temporal coverage of dust information at regional and global scales. Still, there are important gaps in understanding the impact of dust mineralogical composition on various aircraft subsystems.

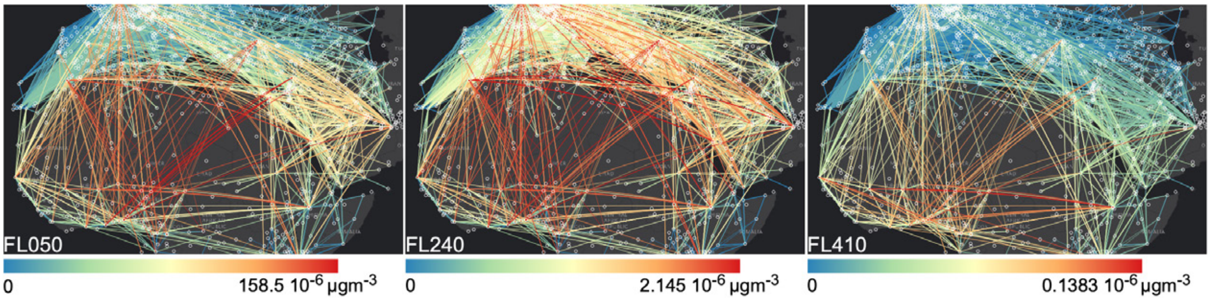

Fig. 5. Climatology of the dust exposure of 9500 commercial flight routes over the region of Northern Africa, the Middle East, and Europe at FL050 (initial climb altitude, left), FL240 (climb/initial descent altitude, middle), and FL410 (cruise altitude, right), indicating the differences in annual accumulative dust particle concentration among routes and flight levels (Votsis et al. 2021).

The location of an airline hub and flight network served by the aircraft operator determine potential exposure to dust hazards across a given fleet. This is due to the geographical heterogeneity of atmospheric dust processes, including horizontal (geographical regions), vertical (altitudes), and temporal (seasons, months, days, hours) elements. As a result, different routes induce different dust exposure and the long-term accumulative effects on engines will vary, depending on the routing patterns. Figure 5, based on Votsis et al. (2021), illustrates with empirical data this link. The graphs shows the annual accumulative particle concentration for approximately 9500 commercial routes over Northern Africa, the Middle East, and Southern Europe at three flight levels. Particle accumulation is indicative of the amount of dust ingested by the engines along different routing choices, which, given Fig. 4, is telling of the influence the origins, routing, and destinations of different flights have on engine maintenance and associated costs.

The above exposure patterns are embedded in a wider context of decisions and factors in commercial airline operations, concerning safety, economics (e.g., fuel and other flight operating costs, maintenance schedules), rules, restrictions, and regulations (e.g., rules on flight planning and performance or safe separation of aircraft in the air), network and airport capacities (e.g., inbound/outbound slots, ATC instructions), or, increasingly nowadays, environmental considerations. It is therefore important to note that optimizing one dimension alone is not realistic. Moreover, in the context of dust hazards, there is a pronounced interplay between day-to-day optimization and long-term accumulative impacts. To adequately understand these, one would need to combine the information represented by Figs. 4 and 5 with cost and benefit data to achieve realistic technical and economic optimization of decisions in operational environments where dust is common. Better information on dust chemical composition would be crucial for this, to translate ongoing research on the type and rate of damage to decision-making.

(b) Identify dust products and services that could enable the flow of relevant information in commercial aviation and in decision-making workflows.

The availability of data and information indicated in (a) should be streamlined by incorporation into the relevant information flows for pilots, operators, airports, and air traffic controllers. An organizational model that can facilitate this aim, in an effective and economically viable manner, is that of meteorological products and services, which can be adapted to develop dust products and services. Perrels et al. (2019) have shown that a healthy and useful market for such services has multiple concurrent information channels that start or end anywhere along the ideal complete pipeline from data producers to end-users, not excluding intermediate users and (re)producers of information. Moreover, a mix of public domain and proprietary information is helpful, with a varying involvement of the public and private sector, where global (ICAO, WMO) and regional (e.g., EASA, FAA, TCCA) public bodies should play key roles (cf. Fig. 1).

One set of such products and services should include the safety and economic factors discussed in section 2: reduced visibility and reduced capacity of airports and ATC to maintain safety, conditions for abrasion and corrosion by dust of engine and aircraft, the prediction of dust melting in turbines, and icing or blocking conditions of critical instruments. Another set should target the influence of dust on air traffic and ground operations, especially the handling and protection of aircraft on the ground, optimized management, and safety of air traffic during SDS events, and flight planning by operators and pilots. A third set should target economic optimization surrounding the maintenance schedule of aircraft, in relation to the types and severities of impacts due the operational environment, as well as the optimization of routing, in relation to fuel and other route costs versus the short- and long-term damage per route choice. The capacities of the destination and alternate airports of a scheduled or en-route flight to accommodate instrument approaches during dust-related events imply safety and economic concerns as well, as they will dictate whether a landing is possible, where to, and via what routing. Lekas et al. (2014) note that the identification of contaminated parts of the airspace during airborne dust transport and the early establishment of uncontaminated air routes will help both operators and air traffic controllers to minimize workload and economic impact and maximize safety. Part of this effort on the dust modeling side should also address the fact that there is major uncertainty when inferring visibility from dust concentration, mostly because of the uncertainties of the particle size distribution and optical properties in the models.

Sections 2 and 3 indicate that the parameter spaces of aviation cost-benefit analysis (CBA) can change by the inclusion of dust impacts. Adding to existing CBA guidelines (EUROCONTROL 2020) the short- and long-term costs of dust should be beneficial. It can provide a link to both private and public sector perspectives, point to the distribution of costs and benefits among key actors, and highlight both short- and long-term cost-benefit optimization perspectives, while also making financial, social, and environmental costs and benefits transparent.

(c) Address the underdeveloped, unclear, or absent role of airborne dust hazards in regulations and operational procedures, as well as in the training, skillset, and knowledge base of pilots.

While better information flows between science, engineering, and decision-making rests on filling scientific data gaps about the effects of dust on aircraft systems and operations, and on developing related products and services, these must also co-evolve with operational procedures, regulation, and the training of air and ground crew. However, it is not clear how.

While METARs, TAFs, and SIGMETs provide a modest start, there are technical barriers to incorporating dust-related parameters into information communication systems, especially once a flight is airborne. The weather radar onboard commercial passenger aircraft does not detect dust, so incorporating dust information into the various data transmission, retrieval, and display protocols and software used in commercial aviation is necessary. However, having dust-related scientific information available somewhere in the loop does not guarantee it will be actively communicated to or utilized by flight crew via their portable (electronic flight bags) or fixed (aircraft avionics) information systems, because dust is currently not perceived as a serious threat and this leads to a largely non-mandatory and non-standardized status for conveying related information. From this perspective, dust information can be made available directly to electronic flight bags and other flight information software or apps, which reach thousands of flight crew daily. It is, however, important to understand that non-mandatory and non-standardized information is a serious obstacle when seen from a human factors angle.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

On the other hand, the recent regulatory response to volcanic ash events showed that "new" atmospheric threats can be incorporated swiftly into existing procedures, but this will require clear communication about the short- and long-term safety and maintenance implications of dust exposure. An approach similar to Volcanic Ash Advisory Centre (VAAC) operations could be adopted as well for monitoring/predicting the atmospheric dust and utilizing the information during the various flight stages. At present, the WMO Integrated Processing and Prediction System (WIPPS) includes two "Regional Specialized Meteorological Center with activity specialization on Atmospheric Sand and Dust Forecast" (RSMC-ASDF, WMO 2021) but these do not have any mandatory function aligned with the aviation sector.

Threat-and-error management (TEM) is an overarching approach to risk management in aviation (ICAO 2002b; Maurino 2005), adopted by ICAO as best practice, and a mandatory component in crew licensing. TEM considers the interaction of human and technical factors when things go wrong, and it is accepted that threats will be amplified if dealt with erroneously and multiple errors align. The combination of multiple layers of threats and errors can lead to undesirable aircraft states (improper handling of the aircraft; incorrect aircraft configuration; wrong ground and air navigational actions), resulting in accidents or (serious) incidents. The objective is to increase the skillsets of ground and air crew to cope with such situations and maintain safe operations. From this perspective, the incorporation of mineral dust information can be in one or more of the aspects of TEM, depending on the impact (cf. section 2) and kind of information (cf. section 3) available. Table 1 provides an outline.

5. Conclusions and outlook

Airborne mineral dust presents an acute hazard for aviation, especially in dust-laden air with significantly reduced visibility. To avoid accidents under these conditions, flights are usually canceled, delayed, or rerouted, which causes an increased workload for airport and airline staff, an inconvenience for passengers, and a considerable economic loss for the aviation industry. In addition, dust causes a substantial cost of maintenance due to deterioration in aircraft and engine performance and in-service life. For instance, Lufthansa Technik (2022) estimated that the engines can deteriorate up to three times quicker in dusty arid regions.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

Table 1. Incorporation of dust information into safe operations via the TEM model (based on Maurino 2005).

SAFE OPERATIONS, eroded by:	
THREATS	**Environmental:** reduced visibility, abrasion & erosion of engine & aircraft, altered aerodynamic profile & reduced efficiency, avionics interference, instrument blockage, icing. **Organizational:** SDS event & increased dust circulation, route & airport hotspots, decreased capacity of air & ground crew.
ERRORS	**Aircraft handling:** unprotected/uncovered aircraft on ground, failure to recognise alteration of aerodynamic parameters, failure to recognise blockage/interference of sensors and avionics, fuel management errors. **Procedural:** engine maintenance tasks & schedule, contaminated runway, unprotected facilities & personnel, ATC/ATM service, inadequate fuel, high-exposure flight plan. **Communications:** omission of dust/SDS from METARs, TAFs, etc., absence of SDS information in onboard information systems, non-reporting of SDS by pilots.
Leading to UNDESIRED AIRCRAFT STATES	

Driven by military operations and economic considerations, the understanding of dust impacts on aircraft systems and aviation operations has improved in recent years. However, while individual effects, such as dust damage to turbine blades, are already well understood from an engineering point of view, they are not necessarily well quantified and cannot be prevented in an operational environment due to missing data (e.g., including important gaps in understanding the impact of dust mineralogical composition in the engines) and the missing information flow from data providers to aviation end users. More information is a requirement also for more realistic and accurate CBA because the inclusion of a better-defined and comprehensive set of dust impacts in the calculations might substantially change the outcome, especially considering accumulated impacts over a longer temporal horizon. Although current CBA guidelines (EUROCONTROL 2020) include categories of costs that are directly impacted by dust (e.g., maintenance and overhaul; fuel and oil; flight equipment insurance, depreciation and amortization; rerouting and cancellation), there is no guidance on what impacts to include, how to monetize them, or indicative unit costs per type of impact. Such information is necessary for a CBA to be sufficient enough for optimizing decisions in dust-laden environments.

There is growing evidence that the responsiveness and vulnerability of turbine engine components to the abrasive, corrosive, and blockage effects of SDP has been increasing due to the increasing operating temperatures inside the engine (Wood et al. 2017). More fuel efficient future engines will drive hotter cores and use more advanced materials, which will be even more susceptible to dust damage.

Impacts of future increasing engine temperatures and increased volumes of air traffic in desert regions range from safety implications to exigent and long-term damage, depending on the duration and concentration of the exposure. This also has significant implications for maintenance schedules and contracts, and the associated costs, as well as for the distribution of responsibilities between at least engine manufacturers and operators. Finally, increased volumes of air traffic in traditionally dusty regions play an important role in these considerations. Increased incidence of dust events combined with increasing volumes of air traffic within and beyond the desert regions will further strengthen the case for dust-related services to be developed and delivered operationally to aviation.

Due to the strong relationship between temperature and damage to engines, climate change with higher ambient temperatures (IPCC 2023) can result in more damage to the engines even with no increase in ambient dust levels. Otherwise, projections of dust emissions in state-of-the-art global climate models are still inconclusive (Aryal and Evans 2021, 2023; Maki et al. 2022; Zhao et al. 2022). Concerns related to the effects of climate change and land degradation are increasing in aviation (Holmes et al. 2024). Besides the increasing frequency and intensity of weather extremes, and other climate hazards (IPCC 2021, 2022), there are increasing risks of favorable conditions for more globally distributed (Vukovic 2019; Vukovic Vimic 2021; Meinander et al. 2022), more frequent and more intensive SDS and other dust-related events (blowing dust, dust devils, long-range dust transport and deposition). Land use and cover change due to agriculture, retreat of glaciers, drying of lakes and rivers etc., can expose land to wind erosion in areas which do not currently recognize SDS hazards and their impacts. For this reason, development and implementation of knowledge of all hazards, including the ones related to airborne dust, is welcomed in all sectors, especially in aviation which targets proactive mitigation measures to prevent great losses in lives and money. On the other hand, the aviation sector should be better recognized as a beneficiary of implementation of climate change and land degradation targets, defined by UNFCCC and UNCCD.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

Acknowledgments. The authors want to special acknowledge the COST Action inDust (CA16202), supported by COST Association (European Cooperation in Science and Technology), and managed by the Barcelona Supercomputing Center (BSC). We thank Diana Urquiza for her designs. The authors also want to thank the DustClim project which is part of ERA4CS, an ERA-NET programme co-funded by the European Union's Horizon 2020 research and innovation programme (grant no. 690462) and the AIRPLAN project funded by the Austrian Research Promotion Agency (FFG), research grant F0999900001. Special mention to the WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) partners and the staff of the WMO Barcelona Dust Regional Center (i.e., the WMO SDS-WAS Regional Center for Northern Africa, the Middle East and Europe jointly managed by BSC and AEMET) for the continuous support to promote research and services. The authors thank the AXA Research Fund for funding the AXA Chair on Sand and Dust Storms (hosted by BSC) and the Belgian Federal Science Policy Office (BELSPO) for their support with the INFRA-FED Programme (contract N° RT/23/NAMSAT). As part of KAIROS EU-Horizon project, this work has received funding from the SESAR Joint Undertaking (JU) under grant agreement N° 101114701. The authors thank the Dutch 4TU Resilience Engineering Programme and the University of Twente Resilience Programme for their continuous support for fundamental research on the resilience of socio-technical systems.

Data availability statement. No new data were created or analyzed during this study and no software (other than for typesetting) was used.

APPENDIX

List of Acronyms

AIRMET: AIRman's METeorological Information. ICAO (2016b, DOC 8400) defines an AIRMET as "Information concerning en-route weather phenomena which may affect the safety of low-level aircraft operations" for radiotelephony communication purpose

ATC: Air Traffic Control

ATIS: Automatic Terminal Information Service

ATM: Air Traffic Management

CAMS: Copernicus Atmospheric Monitoring System

CBA: Cost-Benefit Analysis

DEvAC: Duration of Exposure versus Atmospheric Concentration [chart]

EASA: European Union Aviation Safety Agency

FAA: Federal Aviation Administration

GAMET: General Aviation METeorological forecast. ICAO (2016b, DOC 8400) defines a GAMET as "Area forecast for low-level flights" for radiotelephony communication purpose

IATA: International Air Transport Association

ICAO: International Civil Aviation Organization

ICAP: International Cooperative for Aerosol Prediction

MET: Meteorological information for aviation

METAR: Meteorological Aerodrome Report. ICAO (2016b, DOC 8400) defines a METAR as "Aerodrome routine meteorological report (in meteorological code)" for radiotelephony communication purpose

MRO: Maintenance, Repair, and Overhaul

MTG: Meteosat Third Generation

MWO: Meteorological Watch Office

OEM: Original Equipment Manufacturers

PACE: Plankton, Aerosol, Cloud, ocean Ecosystem

RSMC-ASDF: Regional Specialized Meteorological Center with activity specialization on Atmospheric Sand and Dust Forecast

SDP: Sand and Dust Particles

SDS: Sand and Dust Storms

SDS-WAS: Sand and Dust Storm Warning Advisory and Assessment System

SIGMET: Significant Weather Information. ICAO (2016b, DOC 8400) defines a SIGMET as "Information concerning en-route weather and other phenomena in the atmosphere that may affect the safety of aircraft operations" for radiotelephony communication purpose

TAF: Terminal Aerodrome Forecast. ICAO (2016b, DOC 8400) defines a TAF as "Aerodrome forecast (in meteorological code)" for radiotelephony communication purpose

TCCA: Transport Canada Civil Aviation

TEM: Threat-and-Error Management

UNCCD: United Nations Convention to Combat Desertification

UNFCCD: United Nations Framework Convention on Climate Change

UNEP: United Nations Environment Programme

VAAC: Volcanic Ash Advisory Centre

VOLMET: vol météo (meteorological information for aircraft in flight). ICAO (2016b, DOC 8400) defines a VOLMET as "Meteorological information for aircraft in flight" for radiotelephony communication purpose

WAFS: World Area Forecast Systems

WHO: World Health Organization

WIPPS: WMO Integrated Processing and Prediction System

WMO: World Meteorological Organization

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.

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Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-23-0311.1.

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Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-23-0311.1.