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Observing Mineral Dust in Northern Africa, the Middle East, and Europe

Current Capabilities and Challenges ahead for the Development of Dust Services

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ABSTRACT: Mineral dust produced by wind erosion of arid and semiarid surfaces is a major component of atmospheric aerosol that affects climate, weather, ecosystems, and socioeconomic sectors such as human health, transportation, solar energy, and air quality. Understanding these effects and ultimately improving the resilience of affected countries requires a reliable, dense, and diverse set of dust observations, fundamental for the development and the provision of skillful dust-forecast-tailored products. The last decade has seen a notable improvement of dust observational capabilities in terms of considered parameters, geographical coverage, and delivery times, as well as of tailored products of interest to both the scientific community and the various end-users. Given this progress, here we review the current state of observational capabilities, including in situ, ground-based, and satellite remote sensing observations in northern Africa, the Middle East, and Europe for the provision of dust information considering the needs of various users. We also critically discuss observational gaps and related unresolved questions while providing suggestions for overcoming the current limitations. Our review aims to be a milestone for discussing dust observational gaps at a global level to address the needs of users, from research communities to nonscientific stakeholders.

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Mineral dust impacts on Earth and society

Sand and dust storms produced in arid and semiarid regions can transport mineral dust far away, making mineral dust a global phenomenon. Mineral dust is a major component of atmospheric aerosol affecting many aspects of the Earth system, including climate, weather, atmospheric chemistry, and ecosystems (Prospero and Lamb 2003; Knippertz and Stuut 2014; Shi et al. 2015; UNEP 2020), but also human health and multiple socioeconomic sectors.

Mineral dust affects the Earth's radiation budget directly through the absorption and scattering of solar and terrestrial radiation (Tegen et al. 1996; Haywood and Boucher 2000; Myhre and Stordal 2001; Slingo et al. 2006; Pérez et al. 2006; Balkanski et al. 2007; Miller et al. 2014; Kok et al. 2017; Ginoux 2017; García et al. 2018; Kawai et al. 2021; Kok et al. 2023). By acting as cloud condensation nuclei (CCN) (Levin et al. 1996; Karydis et al. 2017) and ice-nucleating (IN) particles (DeMott et al. 2003; Hoose and Möhler 2012; Murray et al. 2012; Mamouri and Ansmann 2015; Kaufmann et al. 2016; López et al. 2018; Sanchez-Marroquin et al. 2020), dust also influences cloud formation and the associated indirect radiative forcing (Chen et al. 2019; Barreto et al. 2022). A larger number of ice and cloud condensation nuclei existing under favorable atmospheric conditions (Stephens et al. 2004; Creamean et al. 2013; Jiang et al. 2018; Gibbons et al. 2018; Cziczo et al. 2013) may trigger and/or increase the severity of the hazard, such as ice nucleation, high precipitation, and hail (Yuan et al. 2021; Nickovic et al. 2021). This type of dust hazard is still little studied and needs further investigation. Through both direct and indirect effects, dust perturbs the hydrological cycle (Min et al. 2009; Zhao et al. 2011; Skiles et al. 2012; Painter et al. 2012, 2018; Gautam et al. 2013; Matt et al. 2018; Dagsson-Waldhauserova et al. 2015; Wittmann et al. 2017; Dumont et al. 2017; Di Mauro et al. 2019). Mineral dust has both positive and negative impacts on ecosystems (e.g., Okin et al. 2004; Yu et al. 2015; Rizzolo et al. 2017; Gross et al. 2021; Prospero et al. 2020) and the environment (Painter et al. 2012, 2007; Mahowald et al. 2010; Jickells et al. 2005; Arnalds et al. 2014; Ito and Shi 2016). Otherwise, it has been shown that the chemical reactions involving more than one matter phase (i.e., heterogeneous reactions) are paramount among the factors that drive dust's chemical evolution in the atmosphere (Riemer et al. 2019; Schwartz 1986; Dentener et al. 1996; Bauer et al. 2004, 2007; Vlasenko et al. 2006; Fairlie et al. 2010; Karydis et al. 2016). Dust heterogeneous reactions happen mostly when mineral dust mixes with anthropogenic pollutants in urban and industrial areas mostly on the formation of aqueous coatings around the particles (Krueger et al. 2003; J. Li et al. 2009) and the reaction of gases with the particle's surface bulk minerals (Dentener et al. 1996; Goodman et al. 2000).

All these dust interaction processes (i.e., radiative and chemical) are sensitive to dust mineralogy (e.g., Jeong and Achterberg 2014), as dust is, rather than a homogeneous species, a mixture of different minerals with varying physicochemical properties. The chemical composition of mineral dust at local and regional scales depends on the mineralogy of the emitting sources (Claquin et al. 1999; Nickovic et al. 2013, 2012; Journet et al. 2014; Gonçalves Ageitos et al. 2023) as well as on aging in the atmosphere (Scheuvens et al. 2013; Formenti et al. 2011). In this sense, dust emitted from high-latitude dust sources has associated physico-chemical properties that differ from the crustal dust of the Sahara or American deserts (Shepherd et al. 2016; Arnalds et al. 2014; Bachelder et al. 2020; Baldo et al. 2020; Crusius 2021). Mineralogy also affects the hygroscopic properties of atmospheric particles and thus the indirect radiative forcing by dust (Usher et al. 2002), but as well impacts the ice nucleation process (Atkinson et al. 2013; Boose et al. 2016, 2019). Additionally, climate change is one of the potential causes of the increase of anthropogenic sand and dust sources because the increasing temperature could lead to desertification processes extending the dust source, for example, to Europe and high latitudes by the accelerating the melting of the permafrost (Bullard et al. 2016; European Court of Auditors 2018; Dagsson-Waldhauserova et al. 2019; Meinander et al. 2022).

Mineral dust is also recognized as a key player affecting several socioeconomic sectors (Shepherd et al. 2016; Middleton and Kang 2017; Al-Hemoud et al. 2019; Middleton et al. 2019; ESCAP-APDIM 2021; Middleton 2020; Wu et al. 2021; Monteiro et al. 2022). On average in the Middle East and North Africa, welfare losses from mineral dust are estimated in approximately $3.6 trillion USD, where costs are about $150 billion USD and over 2.5% of gross domestic product (GDP) (World Bank 2019). Monteiro et al. (2022) showed that an event of few hours in Crete caused losses of at least 3.4 million euros, showing the potential high impact of such events in long-range transport regions. It is largely acknowledged that mineral dust impacts human health (e.g., Querol et al. 2019; Giannadaki et al. 2014; Goudie 2014; Pérez García-Pando et al. 2014a,b; De Longueville et al. 2013; Karanasiou et al. 2012; Kuciauskas et al. 2018; Pérez et al. 2012; Pu and Jin 2021; Tao et al. 2012; Ueda et al. 2012; Prospero et al. 2008; Derbyshire 2007; Thomson et al. 2006; Yang et al. 2005; Gross et al. 2018; Tong et al. 2023). Short-term effects of high PM10 and PM2.5 (i.e., aerosol particles measured near-ground with an aerodynamic diameter less than 10 and 2.5 μm, respectively) levels include increases in asthma episodes, particularly in children (Cadelis et al. 2014), and mortality due to acute coronary syndrome (Behcet et al. 2018; WHO 2021). The increase of the PM10 and PM2.5 levels can be very high, even in highly polluted cities, for example, in northwest and even southwest China, where Taklimakan dust events have shown to significantly increase mass concentrations of PM10 (11%–173%) and PM2.5 (21%–172%) compared with non-dusty days (X. Li et al. 2018). Long-term exposure to dust episodes may increase premature mortality due to cardiopulmonary effects in the so-called “dust belt” extending from North Africa across the Middle East and South Asia to East Asia (Giannadaki et al. 2014). Dust particles are also associated with morbidity and mortality rates due to respiratory and cardiovascular diseases in regions highly affected by such particles, as in the Canary Islands (Dominguez-Rodriguez et al. 2020), the Middle East (e.g., Al-Hemoud et al. 2018), or Japan (El-Askary et al. 2017). Additionally, dust can carry bacteria, viruses, and spores (e.g., Angulo and González 2007; Ah Sharidah 2021). Dust is hypothesized to be a risk factor for Valley fever (coccidioidomycosis), which is endemic in Arizona and California (Tong et al. 2022) and other parts of Latin America (Hector and Laniado-Laborin 2005; Urrutia-Pereira et al. 2021). Potential infection occurs when a dry spell desiccates the soil-dwelling fungus, and subsequent wind erosion releases the spores (Garfin et al. 2013; Comrie 2005; Tong et al. 2017; Weaver and Kolivras 2018; Comrie 2021). In the African Sahel, dust, low humidity, and temperature have been associated with meningococcal meningitis outbreaks (Pérez García-Pando et al. 2014a,b; Martiny and Chiapello 2013; Oumar Bah et al. 2019; Thomson et al. 2006). Moreover, during dust storms, reduced visibility can cause road traffic accidents resulting in injury and death (e.g., Burritt and Hyers 1981; Novlan et al. 2007; J. Li et al. 2018; Bhattachan et al. 2019; Rawashdeh et al. 2021; AlKheder et al. 2022).

Mineral dust can damage buildings and infrastructure (Miri et al. 2009) but also can cause negative impacts on electricity and solar power generation. Continuous monitoring of the impact of dust aerosols on solar energy has become an important activity at many research and operational centers due to the growing interest in the solar energy industry (Jiang et al. 2011; Mani and Pillai 2010; Goossens and Van Kerschaever 1999; Sarver et al. 2013; Schroedter-Homscheidt et al. 2013; Bergin et al. 2017; Prasad et al. 2022; Fountoulakis et al. 2021; Papachristopoulou et al. 2022). Mineral dust reduces solar irradiance and thus the energy generation potential of solar plants by absorbing and scattering light, reducing the strength mainly of the direct beam (e.g., Kosmopoulos et al. 2018; Hanrieder et al. 2019) or indirectly favoring the formation of high cirrus (Soret et al. 2016; Ilić et al. 2022; Barreto et al. 2022). Moreover, the dust deposition on the solar installations reduces their efficiency (e.g., Costa et al. 2016; Maghami et al. 2016; Wolfertstetter et al. 2014; Rao et al. 2014; Smestad et al. 2020).

Mineral dust can cause significant problems in aviation, such as rerouting due to poor visibility, disturbances in airport operations (including workers’ safety and cleaning installations), and canceling of scheduled flights (e.g., Baddock et al. 2013; Al-Hemoud et al. 2017; Weinzierl et al. 2012; Cuevas et al. 2021; Monteiro et al. 2022), and also has safety and maintenance implications on aircraft operations such as erosion, corrosion, pitot-static tube blockage, melting or engine flame out in flight (Clarkson and Simpson 2017; Lekas et al. 2014). Ice crystals formed by the interaction of dust particles and supercooled water can also block the pitot tubes or sensors on the engine nose cones (e.g., Nickovic et al. 2021). Otherwise, due to increased working turbine temperatures in recent years, the melting of dust in engines and associated problems is as important as the melting of volcanic ash (Wood et al. 2017; Bojdo and Filippone 2019). These identified aircraft’s impacts are a function of exposure time and concentration (e.g., Bojdo et al. 2020), as well as dust mineralogical composition (Bojdo and Filippone 2019).

The effects of dust storms on ground transportation systems (e.g., Miri and Middleton 2022) include traffic accidents associated with the reduction of visibility (e.g., Middleton et al. 2019; Ashley and Black 2008; Lader et al. 2016) and sand and dust on the road (or railroads) can result in vehicle tires losing traction, a tendency to skid and lose control of the vehicle (Pan et al. 2021) and increases the distance. Consequently, the maintenance costs of the infrastructures (i.e., road and railroads) increase.

In semiarid regions, dust storms have many negative impacts on agriculture (Hojan et al. 2019; Hladil et al. 2008) and ecosystems (Arnalds 2015): reducing crop yields by burial of seedlings under sand deposits, the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting, delaying plant development, increasing end-of-season drought risk, causing injury and reduced productivity of livestock, and increasing soil erosion and accelerating the process of land degradation and desertification among others (Stefanski and Sivakumar 2009). The deposition of nutrients is considered among the positive impacts of dust up on both land and marine ecosystems. The deposition of dust benefits marine biomass production in parts of the oceans suffering from a shortage of such nutrients. This could also have a negative socioeconomic impact through the formation of marine algae (Lekunberri et al. 2010) for tourism because of the closing of recreative beach areas or a positive one through the growth of phytoplankton (e.g., Gallisai et al. 2014; Meskhidze et al. 2005) and consequently having impacts on the fisheries management. The mixing of dust with acid pollutants can also increase the solubility of iron and other key metals leading to an overfertilization of the ocean (Rodríguez et al. 2021). Also, dust deposited on snow can deteriorate its quality for sports activities and can cause avalanches (e.g., Dumont et al. 2020; Kutuzov et al. 2019; Monteiro et al. 2022), with consequent potential effects on the winter tourism sector (e.g., ski resorts).

The multiplicity and interdisciplinary nature of the impacts related to mineral dust have aroused considerable interest both in the research community and in different socioeconomic sectors, which call for a better monitoring of the dust cycle (including its emission, transport, and deposition, as well as associated atmospheric and biochemical processes) and for better identifying and quantifying the associated impacts and which can develop mitigation and adaptation strategies to reduce its associated risks.

A common effort toward a global coordination

While there are some positive effects, overall, sand and dust storms have severe negative impacts, particularly in countries downwind of major sources (Middleton et al. 2019; Shepherd et al. 2016; UNCCD 2022) in northern Africa, the Middle East (e.g., Vukovic Vimic et al. 2021; Miri et al. 2009; Sunnu et al. 2008), and Central and East Asia (e.g., ESCAP-APDIM 2021). Although mineral dust emitted in the Sahara during an intense dust storm can reach remote regions such as Europe and Arctic (e.g., Varga et al. 2021; Barkan and Alpert 2010), the Americas (e.g., Denjean et al. 2016; Doherty et al. 2008; Pu and Jin 2021; Prospero et al. 1981; Prospero and Mayol-Bracero 2013; Yu et al. 2019; Zuidema et al. 2019), and Asia (e.g., Park et al. 2005; Sugimoto et al. 2019), emphasizing the global character of this phenomenon. The challenge of mitigating the impacts of sand and dust storms is recognized globally. The United Nations (UN) agencies are promoting measures to confront the problem and their inclusion in national policies through the UN Coalition for Combating Sand and Dust Storms (Pitkanen-Brunnsberg 2019).

Given the scientific importance of mineral dust in the Earth system as well as the numerous socioeconomic impacts, it is clearly reflected in the imperative need to monitor and forecast dust. This is the main objective of the World Meteorological Organization (WMO) Sand and Dust Storm-Warning Advisory and Assessment System (SDS-WAS; WMO 2007). The SDS-WAS searches to enhance the ability of countries to deliver timely and good-quality sand and dust storm forecasts, observations, information, and knowledge to users through an international hub of research and operational communities (Terradellas et al. 2015; Basart et al. 2019). Despite many recent advancements, there is still much to be improved, especially in the harmonization of dust information and the development of dust products tailored to specific applications, which can only be achieved by enabling collaborations among researchers, operational communities, and end-users. This was the main aim of the International

Table 1. Main dust parameters needed for different dust impacts identified in selected socioeconomic sectors.

Dust products	Socioeconomic sector
Vertical distribution	Aviation
Deposition	Agriculture, fishery, ground transportation, aviation, tourism
Icing (dust derived diagnostic related with the dust-IN concentrations)	Aviation, agriculture
PM concentrations in different size ranges (including PM10, PM2.5, PM1)	Air quality, health
Soiling (accumulated dust deposited on the solar plants—this parameter depends on the technology of the solar plant)	Solar energy
Solar irradiance (including dust and clouds effects)	Solar energy
Visibility	Aviation, ground transportation

Network to Encourage the Use of Monitoring and Forecasting Dust Products (inDust; Nemuc et al. 2021). Because of the negative impacts identified in multiple socioeconomic sectors, accurate and adapted dust information is needed. This is a fundamental step for the creation of services that ultimately can support decision-makers and other users. Table 1 overviews the key dust products, already available as operational or sometimes still in research mode, that can be of interest for different communities in identified socioeconomic sectors, while Fig. 1 is a graphical representation of mineral dust impacts on various socioeconomic sectors and related observational products of interest for assessing/managing such impacts.

Benedetti et al. (2018) discussed the observational needs for global aerosol operational modeling and literature reports of recent advancements in the integration of new dust surface parameterization in air quality models (e.g., Klose et al. 2017, 2021). Here, we provide an extended overview of the current dust observational capability from near-surface

1: vertical distribution
2: surface concentrations (i.e. PM)
3: visibility
4: deposition
5: solar irrandiance and cloud effects

6: deposition (including soling)
7: surface concentrations (i.e. PM)
8: vertical distribution
9: solar irradiance and cloud effects
(including icing)

Fig. 1. Graphical representation of mineral dust impacts on various socioeconomic sectors and related observational products of interest for assessing/managing such impacts (see also Table 1). In regions close to the desert dust sources, dust particles can severely affect human health and agriculture, impact the local transportation and cause the closure of airports, and strongly affect solar energy production. At long distances, the presence of dust can affect health, air quality, and solar energy production (reducing solar insolation). Even far away from the source, dust can impact aviation, reducing the lifetime of airplanes and stopping traffic because of visibility reduction. Dust can have also positive impacts on agriculture and fishery because of fertilization capabilities on marine and terrestrial ecosystems. The figure is an adapted version of the inDust leaflet.

measurements to remote sensing observations suitable for user-oriented applications (including monitoring and forecasting) covering Europe and its surrounding regions of northern Africa and the Middle East. Europe is in fact a mineral dust receptor because of its proximity to the largest desert on a global scale (i.e., the Sahara) and long-range transported dust from Asia (especially the Middle East deserts). Also, the European continent has its sources as the one located in countries surrounding the Mediterranean (i.e., Spain and Turkey) and in high latitudes (i.e., Iceland, Norway, Finland, and Greenland). The frequent arrival of dust outbreaks to Europe (particularly affecting southern Europe; see Pey et al. 2013; Gkikas et al. 2016) and the increase of local dust emissions (e.g., Meinander et al. 2022) impacts several socioeconomic sectors, including health, air quality, energy, transportation, and agriculture (e.g., Monteiro et al. 2022; Cuevas et al. 2021). A recent analysis (Gavrouzou et al. 2021) indicates that in the 2005–19 period, the frequency of dust observations from satellites doubled in the Mediterranean area. This emphasizes the need for adaptation to the presence of sand and dust storms considering a broad regional perspective (i.e., including source but also long-range transported regions) and the requirement to build mitigation strategies considering local, regional but also global scales. For all these reasons and considering that Europe contributes to 15% of global gross domestic product (EUROSTAT 2020) and the Mediterranean population is expected to increase to more than 500 million by 2030, socioeconomic impacts are relevant even at global level. All these aspects and the presence in Europe of numerous research infrastructures makes a review of dust observing capabilities and gaps identification from user need perspectives a good starting point for a discussion at a global level about observations and products needed for handling dust impacts and fostering international cooperation on this topic.

This paper reviews the current observational capabilities from a European perspective for the provision of dust information considering the needs of various users (i.e., health, air quality, energy, transportation, agriculture, and tourism). Also, we will discuss the currently unresolved scientific–technological questions and existing observational gaps, providing, when possible, suggestions for their solution. This critical overview is a fundamental step toward setting up a comprehensive global dust observation system, with large geographical coverage and availability of different related parameters, suitable to meet the needs of various users, from research communities to nonscientific stakeholders.

Current capabilities

The mineral dust presence in the atmosphere and its impact on socioeconomic sectors is a complex issue. As reported in literature (e.g., Prospero and Mayol-Bracero 2013; Richter and Gill 2018), synergy among advanced techniques and long-term measurements are needed for increasing our knowledge. To manage and forecast the related risks, improvements in models' capability are essential. Many aspects related to small-scale process in the dust formation [micrometeorology, the effect of soil surface conditions (crusting), fracture mechanics parameterization for dust production, issues with shear stress, turbulence, saltation dynamic], lifting, and transportation are key in this context. This primarily implies the need of multi-instrumental, extended, and long-term measurements in the source region of thermodynamic parameters and soil characteristics including soil moisture, atmospheric dust size distribution, and mineralogy.

A wide range of observational platforms have been utilized to describe mineral loads' spatiotemporal and physicochemical features, which are highly variable due to the heterogeneity of emission, transport, and deposition processes governing the dust life cycle (Schepanski 2018). Two main categories of observational products can be identified: 1) coordinated measurements at network level and satellite datasets, which provide standardized and sustained observations based on well-established protocols for quality assurance and often working on a long-term perspective, and 2) observations in the framework of experimental campaigns providing extensive observations (that usually incorporate innovative experimental setups) at key sites typically during short time periods. They are both precious elements for cutting-edge research and for developing new products. Figure 2 reports examples of advanced observations of desert dust size distribution obtained by aircraft in situ measurements during the Saharan Aerosol Long-Range Transport and Aerosol–Cloud-Interaction Experiment (SALTRACE) 2013 measurement campaign, vertical profiles of volume concentrations for fine and coarse particles obtained combining lidar and photometer observations, and desert dust plume image captured with a very

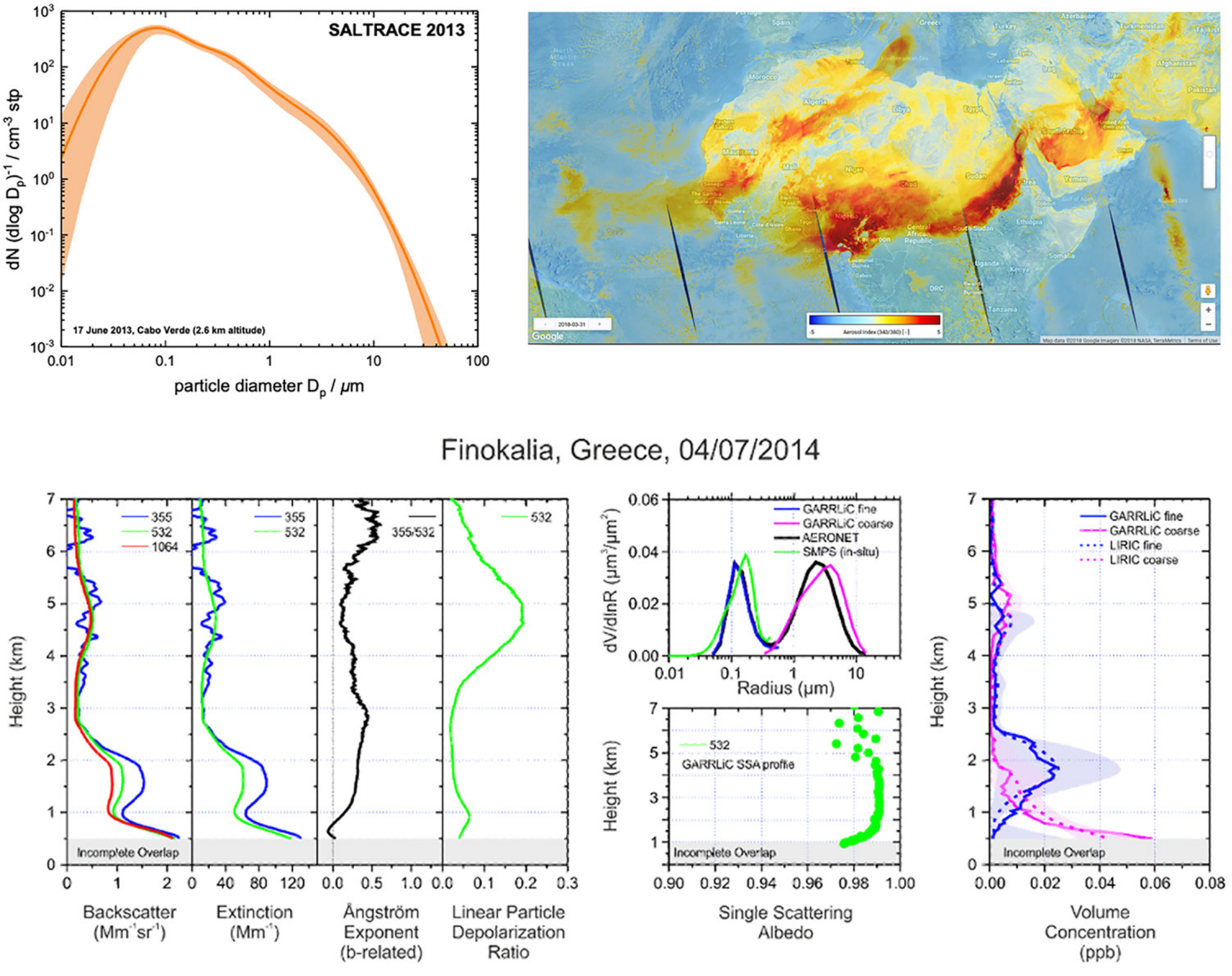

Fig. 2. Highlights of (top left) mineral dust observations from in situ instruments, (top right) satellite observations, and (bottom) ground-based remote sensing techniques. For in situ measurements, the number concentration of mineral particles reported as a function of the particle size as measured from airborne sensors on 17 Jun 2013 in the Cape Verde region during the SALTRACE campaign in 2013 is shown. The dimensional range between 0.01 and about 40 μm is investigated combining different experimental and retrieval methods (Weinzierl et al. 2017). Shaded areas report the uncertainty in the size distribution. The top-right panel shows the satellite image provided by TROPOMI on board *Sentinel-5P* (resolution of 3.5 × 7 km^2) on 31 Mar 2018 capturing a desert dust event with a surprising level of detail. In the bottom panel, lidar data are reported together with lidar–photometer combined products for observations collected at Finokalia, Greece, on 4 Jul 2014 during a dust event. Multiwavelength Raman lidar products are the profiles of aerosol backscatter (three wavelength) and extinction (two wavelength) coefficient, the linear particle depolarization ratio, and the Ångström backscatter related coefficient. The combination of these measurements with collocated photometer observations allows the determination of aerosol size distribution and single-scatter albedo with the GARRLiC retrieval and of fine and coarse volume concentration profiles with both GARRLiC and LIRIC.

tiny resolution by the recently available Tropospheric Monitoring Instrument (TROPOMI) on board the *Sentinel-5P* satellite. Despite that the most common aerosol remote sensing products (as aerosol optical depth and aerosol extinction) are not directly useable for user communities, these products are fundamental for producing accurate and user-oriented dust datasets such as the Dust Constraints from Joint Observational-Modeling-Experimental analysis (DustCOMM; Adebiyi et al. 2020) dataset. DustCOMM combines an ensemble of global model simulations with observational and experimental constraints on the dust size distribution and shape to obtain constraints on four-dimensional (4D, i.e., in space and time) atmospheric dust properties than it is possible from global model simulations alone. For example, ground-based and satellite dust-derived remote sensing products are used to produce model analyses for forecast initialization (Di Tomaso et al. 2017; Escribano et al. 2022) and reanalyses through data assimilation (Di Tomaso et al. 2022) and to evaluate their forecasting skill (Binietoglou et al. 2015; Mona et al. 2014; Yumimoto et al. 2008), as well as further improvements (Georgoulias et al. 2018; Ansmann et al. 2017; Cuevas et al. 2015; Basart et al. 2012; Gliß et al. 2021).

From the ground, valuable information about dust particles' optical (extensive and intensive), microphysical and chemical properties have been acquired from lidars, sunphotometers, and other in situ instruments. Through the deployment and operation of the aforementioned sensors, in which passive and active remote sensing techniques are applied, it has been realized the description of airborne mineral particles' load (i.e., AOD) and nature (i.e., size, absorptivity, composition) at high accuracy but at a local scale. The latter drawback has been complemented to some degree by spaceborne instruments, which provide long-term columnar and vertically resolved dust observations at a global level. Nevertheless, in contrast to ground-based measurements, the primary reliable information is limited, consisting of dust load in optical terms, the identification of mineral particles relying on their depolarization signal, and optical properties related to dust absorptivity. Therefore, the optimum approach toward a better characterization of the dust burden and, subsequently, an improved assessment of the related impacts, requires synergistic actions.

Dedicated campaigns are of great value for developing new methodologies, in particular for multiplatform and multisensor synergistic approaches, and for getting better insight of dust related processes thanks to the extended observational capabilities typically deployed on purposes for specific and focused experiential campaigns (Formenti et al. 2019; Weinzierl et al. 2017).

Here, we report an overview of the current status of coordinated and long-term dust-derived observational products considering remote sensing products (from ground-based networks or satellite platforms), as well as in situ near-surface and aircraft measurements covering the region of Europe, northern African, and the Middle East. Long-term and coordinated measurements are indeed recognized as key, for example, for model validation and development (e.g., Prospero and Mayol-Bracero 2013; Richter and Gill 2018).

We expand the scope of previous reviews, focused on specific techniques and/or platforms for deriving dust information (e.g., Mahowald et al. 2007; Basart et al. 2009; Mona et al. 2012; Rodríguez et al. 2012; Amiridis et al. 2015; Gkikas et al. 2016), by providing a more comprehensive and extended overview, centered on Europe, northern African, and the Middle East, of the current state of observational dust-derived capabilities (at regular basis and at regional scale) focusing on key dust variables for user interests like size-resolved mass concentration, physicochemical properties, and deposition. The data availability review presented here is based on the information collected by the following catalogs:

- the collaborative dust products catalog developed in the framework of the European COST Action inDust and available through the WMO Barcelona Dust Regional Center (i.e., the WMO SDS-WAS Regional Center for Northern Africa, the Middle East, and Europe);

- the overview of satellite aerosol data products (not specific for dust products) of the WMO Global Atmosphere Watch (GAW) Program at the World Data Center for Remote Sensing of the Atmosphere; and
- the observation metadata collection developed within the European Gap Analysis for Integrated Atmospheric ECV Climate Monitoring (GAIA-CLIM) project.

In addition to these observations, the ones performed by the European Facility for Airborne Research (EUFAR; Formenti and Wendisch 2008) and the In-Service Aircraft for a Global Observing System (IAGOS; Petzold et al. 2016) are to be considered as relevant for dust particle observations, providing aerosol data from research campaigns and systematic data collected during in-service flight, respectively.

In situ measurements. A detailed description of methods and techniques mainly used for the in situ near-surface dust characterization is provided by Rodríguez et al. (2012) and WMO (2016) includes the WMO-GAW measurement procedures, guidelines, and recommendations for aerosol measurements, and in particular, for mineral dust. Here, only a brief description is provided, while the strengths and weaknesses of each available dust measurement are shown in Table 2, together with the main networks and programs that provide these data.

To date, PM10 and/or PM2.5 mass concentrations are the most widely used observations to estimate the dust contribution at ground level on a routine basis. These measurements are mostly provided by air quality networks (see Fig. 3a) using automatic instruments [such as beta attenuation gauges, tapered element oscillating microbalances (TEOM), or optical particle sizers (OPS)]. To obtain a rough estimation of the net contribution of dust, the application of ad hoc developed methodologies is required (see, e.g., Gama et al. 2020; Escudero et al. 2007; Barnaba et al. 2022). More robust estimation can be obtained by its chemical composition analysis from particle sampling collection and offline laboratory analyses by techniques such as X-ray fluorescence (XRF), inductively coupled plasma-optical emission spectroscopy (ICP-OES), or ion chromatography (IC). Recently, XRF systems working in real time become available (e.g., Furger et al. 2020). The determination of the mineralogical composition is typically derived from X-ray diffraction of dust aerosol or deposition samples (Marsden et al. 2019; Lequy et al. 2018; Nowak et al. 2018; Engelbrecht et al. 2017; Formenti et al. 2011; Klaver et al. 2011; Formenti et al. 2008; Caquineau et al. 1998), and energy dispersive scanning and transmission electron microscopy of individual dust particles along with statistical cluster (e.g., Ueda et al. 2020; Rodriguez-Navarro et al. 2018; Kandler et al. 2011, 2009; Chou et al. 2008). Both techniques sample mostly the particle surface, which may include coatings of other species. A compilation of measurements of dust mineralogical composition since the 1960s can be found in Perlwitz et al. (2015b). Automatic online analyzers have also been used for short-term (~weeks) campaigns, but these still need technological improvements to be able to provide standardized real-time data on a long-term basis (Furger et al. 2017; Dall'Osto et al. 2004). In addition to the mass concentration and the chemical composition parameters described above, optical properties and size distribution (see, e.g., Fig. 2) are also measured by in situ measurements. The determination of the former generally involves absorption photometers and nephelometers (see references in Rodríguez et al. 2012). The latter requires using at least two instruments: a differential mobility particle sizer (DMPS) and an aerodynamic/optical particle sizer (APS/OPS; Sunnu et al. 2008). Recently, a polarization optical particle counter (POPC), which measures the size and shape (depolarization ratio) of single particles, has also been used for studying the mixing states (external and internal mixing) of dust and air pollution aerosols (Pan et al. 2017; Wang et al. 2017).

Table 2. Strengths and weaknesses related to dust measurements available at ground level. The table also reports in alphabetic order the main scientific networks/programs providing each of the types of dust measurement. Legend: O = operational, R = research, Y = yes, N = no, S = some, RR = registration required.

Parameter	Concept	Strengths	Weaknesses	Network/ programs	Product type (O, R)	Open access (Y, N, RR)
PM bulk concentrations	Dust contribution to the collected PM can be estimated considering that dust particles are big particles and that intrusions are anomalies in the PM records	High spatial density in developed countries	Not able to directly distinguish dust from other aerosol types	ACTRIS in situ	O	Y
				EMEP	O	Y
			Different instruments, measurement techniques and dust contribution calculation methodologies	ESRL	R	Y
				GAW-WDCA	O	Y
			Full-size range of dust not always encompassed by the PM metrics	INDAAF	R	RR
		Standardized measurement within air quality networks		EANET	O	N
			Low spatial density in developing countries	EIONET	O	Y
				EPA	O	Y
				IMPROVE	O	Y
				SPARTAN	O	Y
PM chemical composition	Presence of mineral elements in PM samples allows the dust contribution estimation	Very reliable estimates of dust component	Very expensive and laborious	ACTRIS in situ	O	Y
				EMEP	O	Y
			Difficult to apply routinely	GAW-WDCA	O	Y
				EANET	O	Y
			Limited availability, mostly limited to short-term campaigns	EIONET	O	Y
				EPA	O	N
				IMPROVE	O	RR
Visibility	Visibility in absence of clouds and precipitation is related to aerosol	Good spatial and temporal coverage	Visibility reduction due to the presence of hydrometeors (fog, rain, etc.)	NOAA ISD	O	Y
			Site-dependent relationships	IMPROVE	O	N
Dust deposition fluxes	Deposition on filters or concentration at surface in dust source region can be simply regarded as dust	Heavy measurement load	Limited data availability	CARAGA	R	Y
				EMEP	O	Y
		Data heterogeneity		INDAAF	R	RR
				EANET	O	Y
Dust physical properties	Absorption photometers, nephelometers, APS and OPC instruments derived size distribution	Standardized measurement techniques	Variable spatial density	GAW-WDCA	O	Y
		Distinctive dust optical properties				

An alternative way to infer surface dust concentrations is based on the use of horizontal visibility (inversely proportional to the surface aerosol extinction) data obtained from meteorological reports [meteorological terminal air report (METAR) and synoptic observation (SYNOP)] and empirical equations that relate these data to PM dust concentrations (e.g., Camino et al. 2015). Climatologies based on human-observer reports of dust storms in SYNOPs are discussed in several studies (e.g., Mahowald et al. 2010; Cowie et al. 2014; Klose et al. 2010; O'Loingsigh et al. 2010), along with several issues related to the recording and archiving of SYNOP dust codes (O'Loingsigh et al. 2010), the effects of changes in the interpretation and recording protocols of dust events through time (O'Loingsigh et al. 2014),

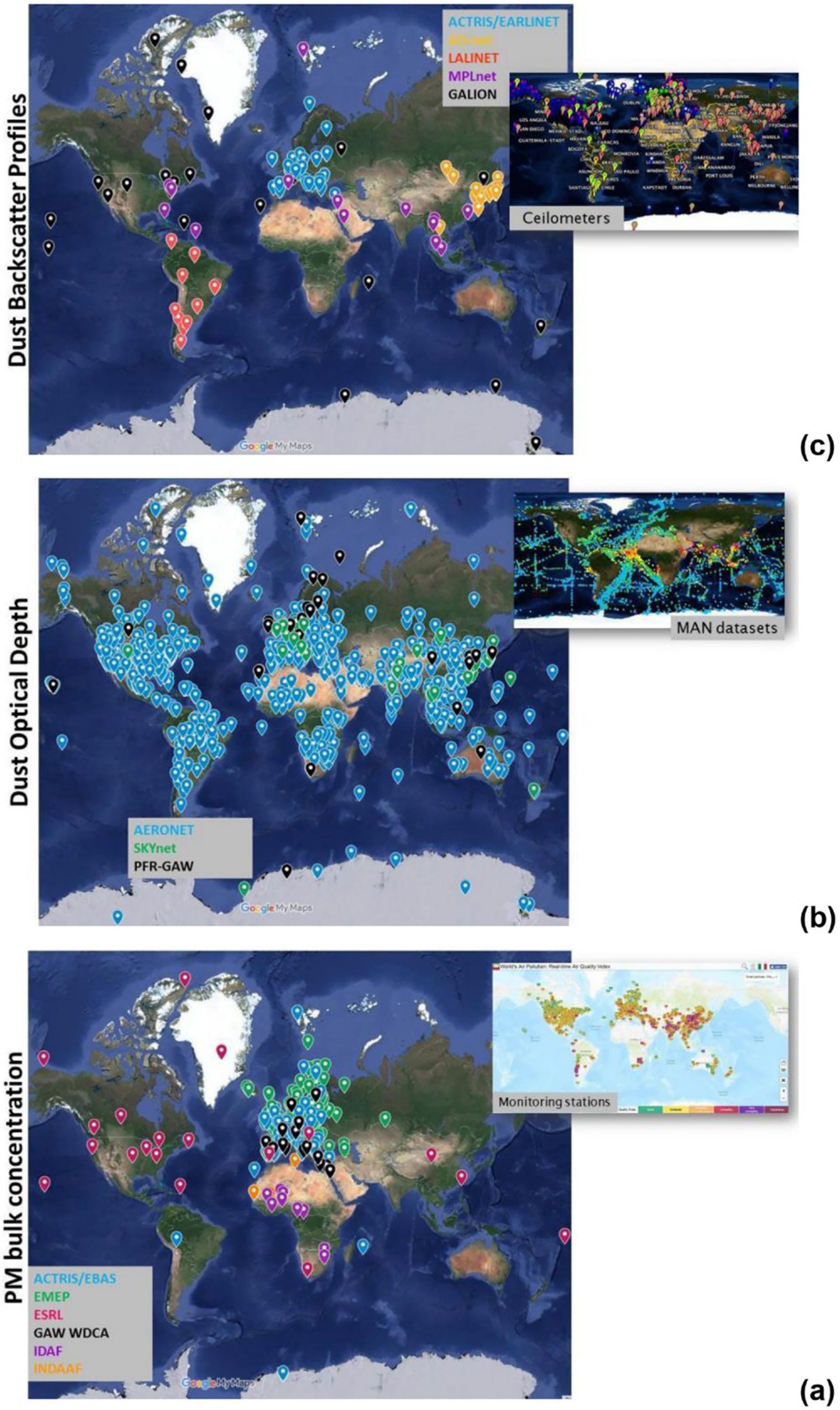

Fig. 3. Geographical coverage of the networks of interest for mineral dust observations: (a) in situ near-surface, (b) photometer, and (c) lidar networks. The inset reports operational corresponding networks for lidar and near-surface observations, while MAN available datasets are reported in the photometer inset as expansion on the sea for the photometer networks present instead on the land. The locations of the stations and datasets are collected from the GAIA CLIM observation metadata collection (https://ciao.imaa.cnr.it/research/projects/#gaiaclim) or from network websites when not available in the GAIA CLIM collection.

and the difference in the reporting of dust events between METAR and SYNOP observers (O'Loingsigh et al. 2017), as well as some difficulties in the classification of dust events (e.g., Dagsson-Waldhauserova et al. 2013, 2014).

Measurements of dust deposition fluxes have been obtained directly by weighting the deposited mass on filters or indirectly from aluminum deposition measurements (e.g., Guieu et al. 2002; Anderson et al. 2016; Laurent et al. 2015; Stuut et al. 2022) or by measuring atmospheric aerosol concentrations and assuming the dust dry deposition velocity and scavenging ratio (e.g., Le Bolloch et al. 1996). Although there have been many studies that characterize the physical and chemical composition of deposited dust, only a few of them have dealt with synthesizing these observations (e.g., Lawrence and Neff 2009). These quantities have been measured in Europe and the Mediterranean basin (e.g., Vincent et al. 2016; Pey et al. 2020; Castillo et al. 2017), as well as northern Africa (e.g., McTainsh 1980; Audoux et al. 2022), during the last 50 years. Dust deposition measurements (both dry and wet) have been systematically provided in the western Mediterranean basin (CARAGA; Laurent et al. 2015), northeastern Spain (DONAIRE; Pey et al. 2020), and the Sahel (INDAAF; Marticorena et al. 2017). Another source of deposition information is the one obtained from paleo records (e.g., McGee et al. 2013) from ice cores, marine sediments, loess-paleosol sequences, lake sediments, and peat bogs as the global compilation of temporally resolved records of dust mass accumulation rates and particle grain size distributions (that help to establish that the data considered represent changes in dust deposition) considered in the Dust Indicators and Records from Terrestrial and Marine Palaeoenvironments (DIRTMAP; Albani et al. 2015) dataset. Such information as dust deposition in ice cores can provide long-term information on the concentrations of atmospheric dust as well as on the strengths of the dust sources and their changes on long temporal scales (e.g., Kutuzov et al. 2019; Varga 2020). The lack of an international standard for deposition sampling (including size resolved deposition) is a limiting factor for the achievement of a harmonized dataset of dust deposition flux. Therefore, more efforts are required for a better understanding of the spatial and temporal variability of dust deposition.

Finally, the investigation of the role of dust in ice nucleation mechanisms and the quantification of the giant coarse dust particles in the atmosphere are cutting-edge topics. For example, aircraft measurements of ice-nucleating particles (INPs) along with chamber laboratory observations (Boose et al. 2016, 2019; Cziczo et al. 2013) are essential for a better explanation of the nucleation processes and for developing INP parameterizations in the prediction of ice and mixed-phase clouds. Data availability is mainly limited to field experiments. An overview of INPs is provided in Kanji et al. (2017), whereas a review of the history of their measurements is reported in Cziczo et al. (2017). Chamber experiments showed how mineralogy, milling, and temperature are key factors in determining the IN properties of dust particles. Importance of organics and crystal water content was also showed (Boose et al. 2016, 2019).

As for giant dust particles (diameter > 20 μm), they have been observed during long-range transport (van der Does et al. 2018) but the explanation of mechanisms behind their presence at large distances from the source is still unclear. More measurements are needed for improving our knowledge and for understanding their specific impacts, for example, on radiation budget, and ice nuclei and grain: specific inlet systems for giant particle samples are needed (Wendisch et al. 2004).

Remote sensing.

Ground-based networks. Remote sensing ground-based networks (Table 3) are based on passive and active remote sensing instruments like photometers and lidars. Photometers are passive sensors that automatically measure the attenuation of the direct solar spectral irradiance due to the aerosols from the top of the atmosphere to the photometer at different

Table 3. Strengths and weaknesses related to ground-based dust measurements using remote sensing. The table also reports in alphabetic order the main scientific networks/programs providing each of the types of dust measurement. Legend: O = operational, R = research, Y = yes, N = no, S = some.

Parameter	Concept	Strengths	Weaknesses	Networks/ programs	Product type (O, R)	NRT (Y/N/S)	24/7 (Y/N/S)	Open access (Y/N)
Dust optical depth	Dust contribution to the AOD (primary measurement) is obtained considering that coarse particles are dust particles	High spatial density in developed countries	Different methods (and uncertainty) in dust component evaluation	AERONET	R	Y	Y	Y
			Cutoff in retrieval algorithm (50 μm) not covering the complete dust size distribution	SkyNet	R	N	Y	Y
		Based on well assessed primary products	Asphericity of the dust particle is still a critical point for inversion products (depending on the used algorithm for the dust contribution estimation)	PFR-GAW	R	Y	Y	Y
			Data are typically limited to daytime condition and not cloudy scenes					
Dust backscatter profiles	Particle depolarization measurements enable to identify the dust component in the aerosol backscatter profiles obtained by lidar measurements	High vertical resolution	No other depolarizing particles considered in the dust attributions	ACTRIS/ EARLINET	R	S	S	Y
				AD-net	O	Y	Y	Y
		Possibility to investigate co-presence of different aerosol type at different altitudes	Different setups mean different assumptions and uncertainties	LALINET	R	N	N	N
			Typically, not available 24/7	MPLnet	R	Y	Y	Y
		Possibility to investigate layer below clouds	Lower uncertainty in nighttime condition	GALION	R	S	S	N
			Low clouds and precipitation inhibit the measurement	E-PROFILE (for ceilometers)	R	Y	Y	N
Dust mass concentration profiles	Dust backscatter profiles are used typically as input for deriving the extinction profiles and then through some assumptions (algorithm) the mass concentration profile	High vertical resolution	30%–60% for Raman/HSRL lidars	ACTRIS/ EARLINET	R	S	S	Y
		Main required information for aviation purposes	Additional uncertainty for backscatter lidars due to further assumptions (lidar ratio)	AD-net	R	Y	Y	Y
		Synergy of lidar and photometer plus retrievals can reduce the total uncertainties	Errors of advanced retrieval algorithms still to be quantified	LALINET	R	N	N	N
			Typically not available 24/7	MPLnet	R	Y	Y	Y
			Lower uncertainty in nighttime condition	GALION	R	S	S	N
			Low clouds and precipitation inhibit the measurements					

wavelengths and provide columnar multiwavelength aerosol optical depth (AOD) and related (aerosol size linked) Ångström exponent (AE) through retrieval algorithms. (e.g., WMO 2016). Recently, daytime condition limitation is overcome by an innovative instrument and algorithm for nighttime AOD measurements (Barreto et al. 2019, 2017). Dust aerosol optical depth (DOD) can be estimated mainly through three approaches: 1) based on the AE value (Basart et al. 2009; Todd et al. 2007; Wang et al. 2004; Dubovik et al. 2002); 2) based on the AOD coarse mode fraction estimated through inversion algorithms (O'Neill et al. 2003); 3) using advanced products obtained by sophisticated algorithms like the Generalized Retrieval of Aerosol and Surface Properties (GRASP) (Dubovik et al. 2014). All three approaches include uncertainties when calculating DOD. While GRASP is a very innovative research methodology and therefore not yet fully characterized in terms of uncertainty, the first approach has the advantage of being applicable for all possible stations because of the AE availability and the low related uncertainties, especially in high AOD regions (as the ones strongly affected by mineral dust). On the contrary, the AE thresholds may filter out some dust intrusions for regions where dust intrusions are sporadic, and other aerosol types are predominant (Cuevas et al. 2015; Di Tomaso et al. 2022). In these regions, the second (coarse mode fraction) approach is the most suitable. In this case, a source of uncertainty is related to the assumption that all coarse mode particles are mineral dust aerosols: other coarse particles like fresh smoke, sea salt, and volcanic ash can be present mixed or not with mineral dust aerosol and therefore contribute to the coarse mode and erroneously be attributed to DOD. Apart from sparse measurements available worldwide, three main networks provide data to estimate DOD (see Fig. 3b): the Aerosol Robotic Network (AERONET; Holben et al. 1998; Giles et al. 2019), the Skynet (Takamura and Nakajima 2004; Nakajima et al. 2020), and the GAW Precision Filter Radiometer (GAW-PFR) network (Kazadzis et al. 2018a). A comprehensive comparison between reference instruments for these three networks showed low AOD differences, demonstrating a promising framework to achieve homogeneity, compatibility, and harmonization among the different spectral AOD networks (Cuevas et al. 2019; Kazadzis et al. 2018b). Alternatively, AOD and AE can be also estimated in the near-infrared (NIR) and shortwave infrared (SWIR) spectral regions from ground-based Fourier transform infrared (FTIR) solar spectrometry (Barreto et al. 2020) which operates within two international networks for atmospheric composition monitoring: NDACC (Network for the Detection of Atmospheric Composition Change; De Mazière et al. 2018) and TCCON (Total Carbon Column Observing Network; Wunch et al. 2011). More recently, these high-resolution FTIR observations have been extended by COCCON (Collaborative Carbon Column Observing Network; Frey et al. 2019), which is a research infrastructure of portable, compact, and low-resolution FTIRs set up as a supplement to TCCON. The Maritime Aerosol Network (MAN), the marine component of AERONET, complements these networks on the land (Smirnov et al. 2009). There are other networks not specifically designed for aerosol measurements, which may provide aerosol and DOD as secondary products like the Australian aerosol network (Bureau of Meteorology Radiation Network and CSIRO/AeroSpan; Mitchell et al. 2017), the National Oceanic and Atmospheric Administration Earth System Research Laboratory's (NOAA ESRL) Surface Radiation Network (SURFRAD; Augustine et al. 2000), the European Brewer Network EUBREWNET; López-Solano et al. 2018), and the Pandonia Global Network.

The lidar technique has the unique capability of providing information on the particle vertical distribution. A detailed review of lidar capabilities for mineral dust investigation is reported in Mona et al. (2012). There are different techniques for investigating aerosol properties using lidar: from the easiest and widely distributed simple, automatic elastic backscatter lidar (e.g., Welton et al. 2001) to the complex and advanced multiwavelength Raman lidar and high spectral resolution lidar (HSRL). A key element for the investigation of mineral dust is the retrieval of the particle depolarization ratio profiles that can be achieved by adding specific detection channel(s) (e.g., Sugimoto et al. 2003). After an accurate calibration of a depolarization lidar system (Freudenthaler et al. 2009), the particle linear depolarization ratio (providing information on the particle shape) allows the discrimination of mineral dust within an atmospheric volume and the consequent derivation of the pure-dust backscatter coefficient profile (Ansmann et al. 2012; Marenco and Hogan 2011) and, in case of Raman/HSRL lidar systems, the dust extinction coefficient profile (Shimizu et al. 2017; Tesche et al. 2009; Yumimoto et al. 2008) and DOD by the integration of the dust extinction profile. Microphysical properties such as the refractive index and size distribution can be retrieved by the multiwavelength Raman and HSRL lidar dataset using sophisticated algorithms to provide higher-level profile products (e.g., Müller et al. 2019).

Ceilometers (elastic backscatter lidars with very low signal-to-noise ratio and different instrumental characteristics in wavelength, laser energy, and resolution) are 24 h/7 day instruments designed for cloud height determination but can be used with certain limitations for aerosol investigation (Wiegner et al. 2014). Backscatter profiles and other higher-level products can be obtained by combining ceilometers and elastic lidars with sun/sky photometers (Berjón et al. 2019; Román et al. 2018; Cazorla et al. 2017; Titos et al. 2019) or with aerosol models (Dionisi et al. 2018). The depolarization capability became recently available for ceilometers and is expected to further enhance the added value of ceilometer measurements, but more research is currently needed to characterize depolarization measurements from ceilometers.

Dust mass concentration can be estimated after the evaluation of dust backscatter profiles: the uncertainty is 30%–60% for Raman measurements but reaches up to 100% in the case of very large particles (>15 μm) and can be even larger for elastic backscatter systems (Ansmann et al. 2012). Indeed, the combination of advanced lidar and photometer observations is found to be highly valuable and meets the need for vertically resolved information on the mass concentration of suspended particles and their fine and coarse components (see example in Fig. 2). Furthermore, the Generalized Aerosol Retrieval from Radiometer and Lidar Combined data (GARRLiC; Lopatin et al. 2013) and Lidar-Radiometer Inversion Code (LIRIC; Chaikovsky et al. 2016) algorithms allow the estimation of fine and coarse mode volume concentrations, which are very useful for distinguishing mineral dust layers in the column (Tsekeri et al. 2017). In addition, a multiwavelength Raman/depolarization system with the addition of a detection channel for Raman return signals from silicon dioxide (used as a tracer of mineral dust) allowed the derivation of mineral dust concentrations in East Asian dust plumes (Tatarov et al. 2011; Müller et al. 2010; Tatarov and Sugimoto 2005). There are several aerosol lidar networks (Fig. 3c) providing coordinated standardized observations at a regional level: the European Aerosol Research Lidar Network/Aerosol, Clouds, and Trace Gases Research Infrastructure (ACTRIS/EARLINET; Pappalardo et al. 2014, www.earlinet.org); the Asian Dust Network (AD-Net; Shimizu et al. 2017; Murayama et al. 2001, https://www-lidar.nies.go.jp/AD-Net/); the Latin America Lidar Network (LALINET; Antuña-Marrero et al. 2017; http://lalinet.org/index.php); and the global NASA Micropulse Lidar Network (MPL-Net; Welton et al. 2001; https://mplnet.gsfc.nasa.gov/). For what concerns dust-related products, the dust partitioning method is incorporated in the real-time AD-Net data analysis system, and the dust extinction coefficient is included in the standard data product (Shimizu et al. 2017). Some prototypes of dust products are currently under investigation in terms of uncertainty and provided in research mode within ACTRIS/EARLINET. Additionally, the feasibility of providing an ACTRIS/EARLINET lidar-derived product for mitigating aviation risks in the case of mineral dust and volcanic ash intrusions has been recently proved (Hirtl et al. 2020; Papagiannopoulos et al. 2020).

As complementary to more advanced lidars, there is a large number of ceilometers distributed worldwide potentially providing valuable information about aerosol vertical layering

(Fig. 3c). Aerosol profile information is being provided in NRT by an increasing number of ceilometers of the E-PROFILE operational network of the European Meteorological Services Network (EUMETNET; Illingworth et al. 2019).

Harmonization and coordination among these regional networks are fostered by the GAW Aerosol Lidar Observation Network (GALION) promoted by the WMO (GAW 2007). Further, GALION cooperating networks are the National Oceanic and Atmospheric Administration (NOAA) Cooperative Science Center for Earth System Sciences and Remote Sensing Technologies (CESSRST, also known as CREST, https://noaacrest.umbc.edu/crest-lidar-network/) lidar network, and the Network for the Detection of Atmospheric Composition Change (NDACC).

Satellite-derived products. Satellite-derived aerosol products have always played a key role in describing the horizontal and vertical distribution of dust plumes. Such information has been acquired, for long-term periods and at a global scale, either by passive or active sensors, providing columnar and vertically resolved aerosol retrievals, respectively. For example, MODIS (Moderate Resolution Imaging Spectroradiometer; Levy et al. 2013) aerosol observations, available since 2000, have been fundamental for aerosol studies and mineral dust investigation (e.g., Boucher et al. 2013; Logothetis et al. 2021). On the other hand, *CALIPSO* (*Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations*; Winker et al. 2009), relying on active remote sensing techniques, depicts the vertical structure of dust layers worldwide since 2006 (Winker et al. 2013; Marinou et al. 2017), through the provision of highly accurate backscatter and depolarization retrievals.

Many operational products are available nowadays from low-Earth-orbiting (LEO) and geostationary (GEO) satellites, which, if harmonized, can fill the observational gaps of the individual sensors thus extending the spatial coverage of dust observations. Indeed, combining the once or twice daily higher information content observations from LEO satellites (currently providing better spectral and/or spatial resolution than GEO satellites) with the high-frequency, lower-information content of the GEO satellites would be of high added value for desert dust research. Table 4 lists the sensors providing dust-related products that are widely used for dust investigation. Through the intercomparison of satellite dust aerosol products, it has been revealed that they often agree well in their dominant large-scale patterns, but not quantitatively or in detail. This is mainly due to differences in (i) information content and technical constraints of instruments, (ii) satellite overpass time, (iii) frequency sampling, (iv) algorithms for aerosol classification, and (v) cloud masking. Significant improvements and evaluation of the different algorithms for aerosol investigation through satellite measurements have been realized, for example, in the framework of the ESA Aerosol_cci project (e.g., Kylling et al. 2018; Sogacheva et al. 2020; Popp et al. 2020).

A critical aspect that must be clarified is that identifying dust from space is not straightforward, especially away from the sources, since the mineral particles are mixed with other aerosol species, and it is difficult to discriminate. Important advancements have been achieved to retrieve quantitative information on desert dust from satellite observations, using features of the mineral particles such as the coarse dimension (threshold on AE; e.g., MODIS); nonsphericity [impact on the phase function and polarization, e.g., Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), or measurements at different angles, e.g., the Along Track Scanning Radiometers (ATSR), the Multi-Angle Imaging Spectroradiometer (MISR), and the Polarization and Directionality of the Earth's Reflectances (POLDER)]; UV/visible aerosol absorbing index [AAI; e.g., from the Ozone Monitoring Instrument (OMI; Torres et al. 2007, 2013) or the Tropospheric Monitoring Instrument (TROPOMI)], allowing to separate absorbing (volcanic ash, mineral dust, and biomass burning) from nonabsorbing aerosols

Table 4. Satellite-borne sensors providing dust-related observations. The table reports the most relevant information about the dust products provision for passive and active (CALIOP, CATS, and ALADIN) sensors, reported in alphabetical order. Legend: O = operational, R = research, Y = yes, N = no.

Sensor	Dust-related variables	Covered period	Resolution	Wavelength (μm)	Product type (O, R)	Open access (Y/N)	Main dust retrieval publications
AIRS	DOD	2003–11	Monthly	0.55; 10	O	Y	Peyridieu et al. (2010)
	Dust altitude				O		
	Effective radius		1° × 1°		R		
ATSR-2/ AATSR	AOD	1995–2012	Daily	0.55	O	Y	Bevan et al. (2012), Poulsen et al. (2012), North (2002), Veefkind et al. (1998)
	Fine mode aerosol optical depth (FMAOD)		1° × 1° and 10 km × 10 km		O		
	DOD				R		
GOME-2	AAI	2007–present	Daily, monthly	0.34–0.38	O	Y	Tilstra et al. (2013)
			1° × 1°				
IASI	DOD	2007–present	Twice a day, monthly	0.55; 10; 11	O	Y	Clarisse et al. (2019), Callewaert et al. (2019), Capelle et al. (2018), Klüser et al. (2015)
	Dust altitude/profile		12 km × 12 km		O		
	Dust parameters (size, mineralogy)				R		
MISR	AOD	2002–present	Subdaily, daily, monthly, etc.	0.55	O	Y	Kahn et al. (2010), Martonchik et al. (2009)
	Aerosol typing		4.4 km × 4.4 km		O		
	DOD (nonspherical fraction)		0.5° × 0.5°		O		
MODIS dark target	AOD	2000–present	5 min, daily	0.55	O	Y	Levy et al. (2013)
			3 km × 3 km		O		
	AE		10 km × 10 km		R		
			1° × 1°				
MODIS deep blue	AOD	2000–present	5 min, daily	0.55	O	Y	Hsu et al. (2004), Hsu et al. (2013), Gkikas et al. (2021)
	AE		3 km × 3 km		O		
	SSA		10 km × 10 km		O		
	DOD (obtained by synergy with external datasets)		1° × 1°		R		
OMI	AOD	2004–present	Subdaily, daily, 32 days	0.35–0.50	O	Y	Torres et al. (2013)
	AAI		13 km × 12 km (24 km)		O		
	SSA		0.25° × 0.25°		O		
			1° × 1°				
POLDER	AOD	2005–13	Daily, monthly, seasonally, yearly	0.44–1.02	O	Y	Dubovik et al. (2014)
	AE		6 km × 6 km		O		
	DOD (coarse)				O		
	SSA		0.1° × 0.1°		O		
	Aerosol mean layer altitude				O		

(*Continued*)

Table 4. (*Continued*).

Sensor	Dust-related variables	Covered period	Resolution	Wavelength (μm)	Product type (O, R)	Open access (Y/N)	Main dust retrieval publications
SeaWIFs deep blue	AOD	1997–2010	Subdaily, daily, monthly	0.55	O	Y	Hsu et al. (2012), Sayer et al. (2012)
	AE		13.5 km × 13.5 km		O		
	SSA		0.5° × 0.5°		O		
			1° × 1°				
SEVIRI	AOD	2004–present	Hourly, daily, monthly	0.55	O	Y	Luffarelli and Govaerts (2019), Clerbaux et al. (2017), Schepanski et al. (2007)
	FMAOD		4 km × 5 km		R		
	Dust index		0.1° × 0.1°		R		
	Dust RGB maps		1° × 1°		O		
SLSTR	AOD	1995–2012	Daily	0.55	O	Y	Bevan et al. (2012), Poulsen et al. (2012), North (2002), Veefkind et al. (1998)
	FMAOD		10 km × 10 km		O		
			1° × 1°				
TOMS	AOD	1979–2004	Subdaily, daily, monthly	0.34–0.38	O	Y	Torres et al. (1998), Torres et al. (2002)
			50 km × 50 km				
	AAI		1° × 1.5°				
			7 km × 3.5 km				
TROPOMI	AAI	2017–present	Subdaily	0.34–0.38	O	Y	Veefkind et al. (2012)
			7 km × 3.5 km				
ALADIN	Backscatter profiless	2018–present	Daily	0.355	O	N	Flamant et al. (2007)
	Extinction profile				O		
CALIOP	Backscatter profiles	2006–present	Daily, monthly	0.532–1.064	O	Y	Amiridis et al. (2013, 2015), Winker et al. (2009), Omar et al. (2009), Zheng et al. (2022)
	Depolarization profiles				O		
	Aerosol typing profiles				O		
	Dust/mixed dust layers				O		
	Pure dust extinction profiles				R (post-processed)		
	Pure DOD				R (post-processed)		
CATS	Backscatter profiles	2015–17	Daily	1.064	O	Y	McGill et al. (2015), Proestakis et al. (2019), Yorks et al. (2016)
	Depolarization profiles				O		
	Aerosol typing profiles				O		

(e.g., de Graaf et al. 2005); or specific spectral signature of desert dust in the thermal infrared [e.g., Infrared Atmospheric Sounding Interferometer (IASI) and Spinning Enhanced Visible and Infrared Imager (SEVIRI)]. Examples of the application of the aforementioned techniques are reviewed hereunder.

The observational capabilities of MODIS and VIIRS (Visible Infrared Imaging Radiometer Suite) have been recently combined with novel retrieval algorithms for dust detection over oceans (Zhou et al. 2020a), in which the nonsphericity of the probed mineral particles (Zhou et al. 2020b) is taken into account. This is also done in the new PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar) retrieval utilizing the GRASP algorithm (Dubovik et al. 2014).

A second example is the unprecedented high spatial resolution (3.5 × 7 km^2) information on aerosol plumes (see Fig. 2) UV AAI, along with height, obtained from TROPOMI on board *Sentinel-5P*. It extends the temporal availability (nearly 40 years) of the corresponding measurements acquired from the TOMS (Total Ozone Mapping Spectrometer) and OMI instruments since the 1980s and 2004, respectively. Positive AAI observations are associated with the presence of absorbing particles (dust or biomass burning) (Herman et al. 1997), and they have been utilized either for the identification of global dust sources (e.g., Prospero et al. 2002) or for monitoring dust activity (e.g., Gassó and Torres 2019).

A third example is the exploitation of the specific sensitivity of thermal infrared (TIR) radiances [as measured, for example, by IASI on board the Metop satellite series, SEVIRI on board the Meteosat Second Generation satellites, Geostationary Operational Environmental Satellite (GOES), Himawari, Geostationary Ocean Color Imager (GOCI)] to mineral aerosols (dust and volcanic ash) through vibrational resonance peaks of silicates (Ackerman 1997), making their observations specific in nature. Qualitative dust products have been obtained from the infrared bands of SEVIRI, GOES, and Himawari in the form of a dust index or a dust red–green–blue (RGB) product (e.g., www.eumetsat.int; Schepanski et al. 2007) covering most of Africa and Europe since 2002. Taking advantage of the high spectral resolution of IASI TIR observations, global long-term (since 2007) daily dust distributions have been obtained with four different algorithms (Callewaert et al. 2019; Capelle et al. 2018; Clarisse et al. 2019; Klüser et al. 2015). However, the TIR observations are sensitive only to coarse mode dust aerosols. In addition, if the DOD is needed at visible wavelengths (e.g., to compare with other instruments) a spectral dependence conversion is needed to convert the TIR coarse mode DOD to visible coarse mode DOD. The TIR instruments also provide observations at night, relying only on Earth's thermal emissions. In addition to the dust optical depth, two operational IASI algorithms provide a mean altitude of the aerosols (Callewaert et al. 2019; Capelle et al. 2018), and one algorithm retrieves vertical profiles with up to 2 degrees of freedom (Callewaert et al. 2019). Both SEVIRI and IASI dust products have been used to analyze dust sources (e.g., Schepanski et al. 2007; Vandenbussche et al. 2020; Chédin et al. 2020), for dust identification and dust plumes' movements (e.g., Banks et al. 2013), and climatological studies (e.g., Banks and Brindley 2013; Banks et al. 2017). Finally, IASI high-resolution spectra can also be used to derive information on the mineralogical composition of dust (e.g., Klüser et al. 2012; Alalam et al. 2022).

The example of recent work on satellite dust-specific products is the Lidar Climatology of Vertical Aerosol Structure for Space-Based Lidar Simulation Studies (LIVAS) study of the European Space Agency (ESA), using CALIOP 532-nm backscatter and depolarization products in synergy with the ground-based typical values of mineral particle depolarization and lidar ratios (i.e., the extinction-to-backscatter ratio) derived from EARLINET (Amiridis et al. 2013, 2015). LIVAS delivers pure dust optical depth and extinction profiles useful for describing the 3D transport of dust over Europe (Marinou et al. 2017), the 3D structure of dust over Southeast Asia (Proestakis et al. 2018), and dust ice-nucleating particle concentrations (Marinou et al. 2019). A similar approach can be followed for deriving pure-dust products from the NASA Cloud-Aerosol Transport System (CATS) mission (Yorks et al. 2014) on board the International Space Station (ISS), which operates at 1,064 nm. Vertical profiles of aerosol extinction and backscatter are also provided by the ongoing *Aeolus* mission

(Kanitz et al. 2019; Straume et al. 2019) and are expected from the forthcoming Earth Cloud, Aerosol and Radiation Explorer (EarthCARE; Illingworth et al. 2015) mission of the ESA, at 355 nm, and furthermore from the Atmosphere Observing System of NASA at 532 nm. These missions will substantially upgrade the altitude-resolved observational capabilities in the troposphere and stratosphere. In contrast to CALIOP, the High Spectral Resolution Lidar (HSRL) Atmospheric Laser Doppler Instrument (ALADIN) and the Atmospheric Lidar (ATLID) instruments on board *Aeolus* and EarthCARE, respectively, will acquire vertical profiles of aerosol optical properties without requiring a priori assumption of the lidar ratio. However, in the case of ALADIN (Flamant et al. 2007), degradation of its performance for the backscatter (underestimation) and lidar ratio (overestimation) is expected when nonspherical mineral particles are recorded due to the misdetection of the cross component of the return lidar signals (Gkikas et al. 2023).

Beyond the measurement techniques applied for dust retrievals from space, multisensor and/or multiparameter approaches have been suggested for identifying dust presence and contribution to total AOD. A promising approach for deriving DOD from columnar AOD has been demonstrated through the synergistic implementation of spaceborne retrievals and reanalyses/model outputs. Gkikas et al. (2021, 2022) developed a global fine resolution (0.1° × 0.1°) dataset [MODIS Dust Aerosol (MIDAS)], over the period 2003–17, via the combination of MODIS-*Aqua* AOD and Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), dust fraction. A similar methodology was applied by Ridley et al. (2016), who adjusted the bias-corrected coarse-resolution AOD, derived by multiple satellite platforms, to DOD by utilizing the dust contribution to the total load, in optical terms, simulated by four state-of-the-science global models, over 2004–08. Recently, Voss and Evan (2020) provided a long-term record of DOD relying on MODIS (2001–18) and AVHRR (Advanced Very High-Resolution Radiometer; 1981–2018) AOD retrievals, AERONET fine mode fraction, and MERRA-2 wind fields. Synergistic use of different sensors offers the possibility for accurate dust identification as recently demonstrated by the combined use of lidar and infrared imaging radiometer on board *CALIPSO* (Zheng et al. 2022).

It is important to mention that some follow-up sensors will continue those dust-related observations. In some cases, the successor instruments are already in orbit such as *Suomi NPP* [Visible Infrared Imaging Radiometer Suite (VIIRS)] replacing MODIS and the Sea and Land Surface Temperature Radiometer (SLSTR) for the Advanced Along-Track Scanning Radiometer (AATSR), while in other cases they are scheduled within the next few year, such as the Multi-viewing Multi-channel Multi-polarization Imaging (3MI) for POLDER, Infrared Atmospheric Sounding Interferometer, New Generation (IASI-NG) for IASI, the Infrared Sounder (IRS) for SEVIRI in the Meteosat Third Generation (MTG) series, and the EarthCARE for CALIOP and CATS. Potential new insight will be offered by the NASA PACE (Plankton, Aerosol, Cloud, Ocean Ecosystem) mission planned for launch in 2024 (Werdell et al. 2019). Through polarimetric observations, PACE will provide, among other variables, aerosol fine fraction and therefore also an indication of the presence of dust which combined with ocean products, will reveal how dust might fuel phytoplankton and algae growth at the ocean surface. The recent launch of the Earth Surface Mineral Dust Source Investigation (EMIT) mission (Green 2022) will bring more information on the mineralogical composition of dust over the sources, while the Atmosphere Observing System (AOS) of NASA (Vane et al. 2022) is expected to provide more advances on dust retrievals from forthcoming multisensor synergies.

The way forward: Gaps and recommendations

The current maturity of the observational and forecasting systems for monitoring and forecasting sand and dust storms allows for a better identification and assessment of dust-related impacts on socioeconomic sectors and, consequently, allows for the definition of the user's needs. This is a fundamental step for the design and creation of services that can support reducing the negative impacts of dust occurrences and enhancing the positive ones. The improved observational capability opens new frontiers and poses new scientific questions, increasing the level of request and need for observational capabilities. Nonetheless, there are still gaps in the observational system and room for improvements, as described hereafter.

Scarcity of observations. Satellite measurements described above provide global information on dust plumes, but they require more precise ground-based instruments for their validation under all possible conditions and as a reference for harmonizing datasets from different sensors/satellites. Additionally, satellites do not provide all the dust parameters of interest, making ground-based remote sensing and near-surface measurements essential. Figure 3 shows a very good coverage in coordinated measurements in the Northern Hemisphere, yet a limited number of available ground-based observations close to the main mineral dust source regions. Few observations are also available for the high-latitude dust sources, contributing at least 5% of the global dust budget (Bullard et al. 2016; Meinander et al. 2022). In this respect, it must be underlined here that the reported geographical coverage can suffer from missing information. This, however, underlines that in the case of available measurements, there is still a gap in their advertisements and a need to strengthen the link between the different regions.

The lack of ground-based measurements in dust-source areas, as well as the lower reliability of dust satellite products over the typically bright source areas, introduces limitations from several points of view: for improving understanding of the processes of dust generation and its injection into the troposphere, for the initialization of dust models, then for the model assimilation and evaluation, and finally for the analysis of dust impacts in the most affected dust regions. Additionally, these areas are crucial for satellite validation because of an often-complex vertical distribution and high temporal and spatial variations. For example, AOD datasets from FTIR could be, as well, a valuable validation system for satellite sensors incorporating IR spectral bands, as IASI on board the EUMETSAT/Metop platforms, or the Operational Land Imager (OLI) aboard *Landsat-8*, and VIIRS aboard *Suomi NPP*. In addition, some recent works have demonstrated the potentiality of low-cost radiometers (Almansa et al. 2017, 2020) and all-sky cameras. All-sky cameras can retrieve AOD by applying GRASP (Román et al. 2017; Antuña-Sánchez et al. 2021; Román et al. 2022; Antuña-Sánchez et al. 2022). The main advantage these all-sky camera retrievals offer compared to photometers is to select alternative sky points when clouds contaminate the standard sky points from hybrid or almucantar scans of sunphotometers. Ground-based aerosol measurement networks worldwide are generally motivated for the purposes of air quality and health and specific adverse PM effects on human populations. Therefore, PM measurements are generally collected where the people are in cities, and not in dust source areas which are almost all far removed. There is also a lack of coordinated deposition measurements. Distributed instrumental deployments such as those of the CARAGA (Collecteur Automatique de Retombées Atmosphériques insolubles à Grande Autonomie) deposition collector (Laurent et al. 2015; Vincent et al. 2016) should be widely applied to improve the availability of total (dry and wet) atmospheric deposition of insoluble dust in remote source areas. At the international level, common measurement protocols for deposition must be established to have comparable databases and to better constrain deposition budgets.

Specific and reliable measurements of deposition and simultaneously of aerosol/cloud vertical resolved profiles supporting new products such as the aerosol–cloud coincidences based on dust model reanalysis could be of interest in areas like North Africa, where the solar energy production potential is very high due to infrequent cloudiness and high insulation, and dust is a serious mitigating factor, would also facilitate the management of solar power plants, including the planning of new facilities. This observational gap is hard to fill, especially in North Africa, due to challenging political and socioeconomic conditions, as well as, in more general terms, due to the extreme environmental and operational conditions (high temperatures, access to electricity). Specific instrumental adaptations and approaches for reducing expensive maintenance and operation costs are needed.

A potential solution for filling this observational gap is the development of Lower-Cost Medium Precision (LCMP) instruments, as the zenith looking narrow-band radiometer (Almansa et al. 2017, 2020), with no mobile parts, specifically designed to measure desert dust, and land low-cost sensors operated by national weather services or even transportable on unmanned vehicles or drones (e.g., Morys et al. 2001; Guirado et al. 2014; http://www.calitoo.fr; Pikridas et al. 2019; Kezoudi et al. 2021). These instruments could benefit from more advanced instrumentation for testing, validation, and quality assessment (Giordano et al. 2021). Otherwise, the support of research infrastructure, networks, and international initiatives, such as ACTRIS and WMO SDS-WAS, will be key for developing those activities. A global coverage can be provided at a certain level of confidence only through integrating satellite global measurements with models through reanalysis procedures: although reanalyses cannot be considered a replacement for long-term observations, they provide no-gap datasets covering the whole globe at an increasingly higher spatial resolution. Examples of such reanalyses, including dust estimates, are the Copernicus Atmosphere Monitoring Service (CAMS) Interim Reanalysis (Inness et al. 2019; Flemming et al. 2017) and MERRA-2 (Gelaro et al. 2017; Randles et al. 2017).

Hidden small-scale, short, and intense dust storms. There are several meteorological mechanisms involved in the occurrence of sand and dust storms, each with its own diurnal and seasonal features, occurring at a wide range of spatiotemporal scales (i.e., synoptic, mesoscale, and microscale) that may control strong winds and cause dust storms (Knippertz and Stuut 2014). Overall, global and synoptic-scale sand and dust storms are well tracked by satellites and models. Meanwhile, our knowledge about the occurrence and contribution to the global aerosol budget of smaller-scale phenomena, such as dust devils and haboobs, is limited (e.g., Jemmett-Smith et al. 2015; Marsham and Ryder 2021). Haboobs are often caused by an atmospheric gravity or density current, such as thunderstorm outflow, but can also occur as a result of strong synoptic gradient winds, such as following a dryline or dry frontal passage. A haboob may transport huge quantities of sand or dust, which move as a dense wall that can reach a height of 1,000 m (about 3,300 ft) and more, has a lifetime of several hours, and can cause important damage (e.g., Vukovic et al. 2014; Rooney 2017; Vukovic Vimic et al. 2021). Local, short, and intense convective dust storm development, movement, and shape are difficult to be estimated using satellite data because of the presence of clouds in these systems, creating a gap in the nowcasting (e.g., Dempsey 2014; Vukovic Vimic et al. 2021) and hazard management for such cases, but also, because the dust clouds are generally carried within the boundary layer or otherwise very close to the ground where satellite dust detection is typically difficult. Additionally, only geostationary satellites with high-temporal resolution (as MSG, <15 min) can be considered for nowcasting. Radars with dual-polarization technology have the ability to characterize these events by combining reflectivity, Doppler velocity, and co-polar correlation coefficient (i.e., the correlation between reflected horizontal and vertical polarized signals from each scatterer in a volume sample). Some urgent issues for improving information acquired in the dust forecast models have been identified. A haboob's forecast quality depends on the explicitly resolving of the convection (Vukovic et al. 2014; Gasch et al. 2017; Vukovic Vimic et al. 2021), which is highly dependent (i.e., spatial resolutions of a few kilometers) on the model resolution and the dust source definition (Vukovic et al. 2014; Vukovic Vimic et al. 2021). On one hand, some efforts have been made for the development of more simple parameterizations of haboobs for models with parameterized convection, based on the downdraft mass flux of convection schemes (see Pantillon et al. 2016). On the other hand, the sensitivity of forecast quality of such severe dust events to surface data proves that dust sources need regular updates using high-resolution (<5 km) observations [e.g., normalized difference vegetation index (NDVI) or enhanced vegetation index (EVI), as well as land cover and soil moisture data observed by satellites]. There is a need to identify specific dust source types such as alluvial sources that have been identified as particularly active, in addition to dry lake beds (e.g., Feuerstein and Schepanski 2019). Dried lakes and glaciogenic sediments that may increase because of changing climate conditions can provide small-scale dust sources that must be identified. Such identifications have so far been frequently obtained by visual identification of dust plumes in satellite images of desert surfaces. It has been estimated that anthropogenic playa sources (i.e., the exposed beds of shrinking water bodies) contribute 85% of global anthropogenic dust emissions (Zucca et al. 2021). Land degradation and desertification processes play an important role on dust emission from playa sources which is frequently triggered or increased by human activities such as unsustainable land and water use upstream, reduced vegetation cover on and around playas, and mechanical disturbance of the playa surfaces. The problem of appropriate high-resolution specification of dust sources has been recognized by the United Nations Convention to Combat Desertification (UNCCD) as a major problem in the management of hazardous conditions. In this context, UNCCD promoted the development of a global high-resolution dust source database, the Sand and Dust Storms Source Base-map, as a part of the work considered in the Sand and Dust Storm toolkit coordinated by UNCCD (2022). Another critical local phenomenon is the formation of nocturnal low-level jets related to the reduced surface friction during stable nighttime conditions—a process typically underestimated by models because of a poor boundary layer description (Fiedler et al. 2013). This may be improved by increasing the number of meteorological observations but also requires model development, specifically concentrating on arid areas. International actions are needed to improve both dust aerosol and meteorological networks, possibly with low-cost sensors, and to develop specific strategies for maintaining continuity of observations in remote or extreme environments.

Missed physicochemical dust properties. Improving the description of the chemical composition is urgent for various applications, including climate and weather modeling. The availability of more size-resolved measurements of dust chemical composition, particularly close to the source regions, would be beneficial for understanding and better quantifying the dust impact. The degree of abrasion and melting that an aircraft suffers is a function of exposure time, dust mineralogical composition, and its concentration. Each mineral has its own physicochemical characteristic regarding hardness (Clarkson and Simpson 2017) and melting points (Wood et al. 2017). Feldspars and quartz (Atkinson et al. 2013; Harrison et al. 2019; Ilić et al. 2022) are efficient ice nuclei. The increase of ice nuclei due to the presence of dust has direct implications for solar energy (i.e., cirrus formation) and aviation (i.e., icing). The mineralogy can help to advance our understanding of the role of dust in health (WHO 2021) and agriculture (e.g., Stefanski and Sivakumar 2009; Zia-Khan et al. 2014). Focusing on current activities on mineralogical modeling at regional and global scales, it is also important to mention the need for detailed and high-resolution (<1 km) global databases of soil physicochemical properties and textures, which are commonly used in soil classification systems such as those reported by the UN Food and Agricultural Organization (FAO) Digital Soil Map of the World (DSMW; FAO 1974; Batjes 1997) or the Harmonized World Soil Dataset (HWSD; Nachtergaele et al. 2009) both at a spatial resolution of ~10 km at midlatitudes. Here it is worth mentioning that combining both versions of DSMW (from 1974 and 1997), there are a total of

211 different soil units with potential mineralogical content. Soil map composition from Claquin et al. (1999), Nickovic et al. (2012), and Journet et al. (2014) represents the initial efforts to represent the mineralogy by mode. These works identify 8 and 12 minerals relevant for various dust impacts (e.g., to climate, marine productivity, cloud formation), in the clay and silt fractions of the soil. The accuracy of model representations of the mineral dust composition linked to soil mineralogy is expected to be drastically improved by novel hyperspectral imaging spectroscopy over the coming decade thanks to the NASA EMIT (Green 2022) and the German Environmental Mapping and Analysis Program (EnMAP; Chabrillat et al. 2022) missions. The resulting spectroscopically derived mineral composition will be used to update the dust source region initialization of models (Green 2018) and will enhance the current efforts of the atmospheric research community to better represent and understand dust mineralogy (Perlwitz et al. 2015a; Scanza et al. 2015; Pérez García-Pando et al. 2016, 2019). A recent paper (Go et al. 2022) showed the possibility to use the EPIC (Earth Polychromatic Imaging Camera) measurements as a tool for retrieving hematite and goethite concentrations in pre-identified dust plumes, providing important information about dust composition.

Other initiatives such as the European Research Council (ERC) projects FRAGMENT (Frontiers in Dust Mineralogical Composition and Its Effects Upon Climate; Pérez García-Pando et al. 2019) will provide complimentary ground- and laboratory-based observations and analyses of soilborne and airborne dust composition needed to develop the parameterizations of the soil-to-aerosol transfer functions.

Dust size distribution is also key for understanding the effects of dust (e.g., Kok et al. 2017). Mineral dust has a wide dimensional range from fine (Fratini et al. 2007) to giant particles (Ryder et al. 2019). Typically, attention is focused on the coarse mode of mineral dust because it is the most abundant, but fine fraction, even if smaller as an aerosol load, is an important fraction because of its potential impacts on the health: the smaller the particles, the deeper they penetrate inside the human body. The presence of giant particles is typically neglected in the study of mineral dust plumes, but recent studies suggest that these particles should be considered (van der Does et al. 2018; Varga et al. 2021). Giant particles are commonly found over the Mediterranean ($D > 40\ \mu$m in the 2.5–4-km altitude range and $>80\ \mu$m below), over the Atlantic ($>75\ \mu$m in the Saharan aerosol layer) (Ryder et al. 2019; Marenco et al. 2018; Renard et al. 2018; Betzer et al. 1988), in the Caribbean (20–30-μm particles) (Weinzierl et al. 2017), and in the Arctic (up to 90-μm Saharan quartz particles) (Varga et al. 2021). These large particles may be of high importance because they can act as giant cloud condensation nuclei (GCCN) and ice nuclei (IN), determining the concentration of the initial cloud droplets, the clouds' albedo and lifetime, and the precipitation formation, especially through warm rain processes (Koren et al. 2012; Feingold et al. 1999; Eagan et al. 1974). In a recent study, Ryder et al. (2019) showed that omitting giant particles leads to a significant underestimation of shortwave and longwave extinction over the Sahara. However, the main remote sensing instruments used nowadays in measuring aerosols (i.e., lidars and photometers) cannot retrieve aerosol microphysical properties for particles larger than a few microns (Müller et al. 2012), while cloud radars seem to be able to detect giant particles also at a large distance from the source (Marenco et al. 2018; Ryder et al. 2018; Madonna et al. 2013, 2010). First simulation studies show that cloud radar can detect mineral particles with a minimum effective radius of about 50 μm and number concentrations larger than 0.1–1.0 cm^{-3} (Madonna et al. 2013), while smaller particles down to a few microns can be detected in the presence of higher number concentration in the 20–130 cm^{-3} range (Guma-Claramunt 2016). Further investigations on this topic are needed, but it is clear that a synergistic use of photometer, aerosol lidar, and cloud radar could open new opportunities to measure and study the presence of dust in the whole relevant dimensional range.

Additional ground-based and airborne in situ measurements of the size dust spectrum (from ultrafine to large giant particles) are needed. For in situ ground-based and airborne measurements of giant particles, specific inlet systems should be used, and the detection of the whole dimensional range has to be obtained by integrating different methods (Wendisch et al. 2004). Ultimately, a better description of the dust physicochemical properties will deal with a better characterization of some key parameters used for monitoring sand and dust storms, such as visibility, AOD, or extinction provided by models or remote sensing retrievals.

What are the users looking for? The several impacts of dust have led to a growing interest from various stakeholders—such as air quality managers, health professionals, solar energy plant operators, aviation, and policy makers—for dust products tailored to their specific needs. The undertaken actions through inDust (Nemuc et al. 2021) for better connecting researchers and user communities allowed for a first identification of needs and requirements per socioeconomic sector. There is a clear and general interest to have regionally and time-resolved chemical characterization of mineral dust to improve our understanding on the identification of dust impacts on ecosystems, as well as, on agriculture, fishing, and tourism (skiing and beach activities). More specific requests from sectors more advanced in the assessment of the dust impacts are as follows:

- For health, the first is a lack of monitoring in many countries of the world and inadequate monitoring in rural areas or outside of major cities in many countries; second is the lack of standardized dust-related measurements (including size distribution and chemical composition) to perform assessment studies that can contribute to understand the different relationships between dust and health impacts (i.e., differences in composition of tropical versus high-latitude deserts, or the enhancement of some atmospheric chemical reactions that can increase the pollution levels).
- For air quality management, one of the current main difficulties is related to the methodologies applicable for quantifying the mineral dust contribution to the total PM10/PM2.5 and PM1 concentrations observed, typically based on back-trajectories analyses, forecast, and satellite image analysis and gravimetric measurements (Querol et al. 2019; Barnaba et al. 2022). There are some heterogeneities and/or difficulties in applying such methodologies, particularly in near-real-time (NRT) scales. Moreover, a relevant concentration of mineral dust particles larger than 10 μm in size can be observed (Reynolds et al. 2016). Even if less severe with respect to smaller particle ones, >10-μm particles could have an impact on human being wellness, which investigation can require to go further respect to standard air quality measurements of PM10 and PM2.5 (Reynolds et al. 2016). Particular attention should be paid when the PM is measured with instruments based on different methods (i.e., gravimetric and equivalent methods) and take into account the influence that the wind speed could have on the measurements even when using the same type of instrument, especially in conditions of high wind speed (Sharratt and and Pi 2018). Novel XRF spectrometers providing chemical composition of PM in different size classes (Furger et al. 2020) could be relevant for improving source apportionment, but are still research systems available in few laboratories.

  Alerts based on the magnitude of dust events (based on monitoring and modeling results) could help local authorities to manage the effects related to such events, for example, by reducing anthropogenic emissions on critical days. A good example is the Dust Warning Advisory System provided by the WMO Barcelona Dust Regional Center developed in the framework of the WMO CREWS project. Finally, a better understanding of the role of dust in atmospheric chemistry can deal with the improvement of air quality forecasting systems.

- For transportation, visibility is widely used because it is directly connected with safety protocols. Accurate forecast of dust visibility requires a better understanding of the role of optical properties and size distribution (particularly the contribution of giant particles at sources). In particular, for aircraft maintenance, 4D concentration, chemical and size-resolved atmospheric dust properties are demanded to advance the understanding of dust impacts on the engines. Furthermore, for safety and cleaning management of the infrastructures (i.e., airports, roads, and railroads) estimates on the dust deposition are required. In this framework, PM and dust deposition routinely measurements at airports could support the management of the visibility-related risks at airport and improve the assessment of the visibility and dust deposition forecast.
- For solar energy, meanwhile more accurate solar irradiance forecasts (including the direct and indirect effect of the presence of dust) are being considered by different European providers (as Copernicus), soiling information is still far from being available for the final user in a solar plant. Current soiling information is scattered in solar plants around the world and there are no standards for their measurement. Therefore, the available soiling measurements are highly dependent on the technology (e.g., solar concentrated or photovoltaic) used in the measurement point (i.e., solar plant). To overcome this limitation, it would be desirable to incorporate simultaneous deposition, surface concentration and soiling measurements in solar plants.

To bring things together

In recent years, developments in Earth observation, fostered by coordinated international initiatives and programs such as WMO SDS-WAS, led to great advances in the observational capabilities of mineral dust particles. Wide collected information opens new possibilities for facing the increasing request of tools for improving management and resilience of dust related impacts, more and more relevant because of climate change. This paper aims to be a milestone in matching available information and knowledge demand, providing an overview of current dust observations and taking into consideration first collected user needs.

Here, we seek to provide an overview of the state-of-the-art of operational and distributed observations in northern Africa, the Middle East, and Europe. Potential developments are underlined and highlighted in view of the user needs currently identified thanks to the inDust international initiative. Observational gaps are identified in terms of coverage but also of specific information like additional data about deposition (wet and dry), visibility, dust vertically resolved information, dust chemical composition, and giant particle presence.

First, the most relevant source regions are scarcely equipped with instruments for dust monitoring. The situation could be improved through the support of international initiatives like WMO SDS-WAS and UN coalition, and the use of low-cost sensors for key information acquisition (deposition, visibility, and meteorological parameters). Research infrastructure, networks, and international initiatives should support such activities, providing a platform for checking and validating low-cost sensors. The latter is crucial for improving the models in terms of accuracy and uncertainty evaluation in the vertical dimension. Additionally, satellite observations are currently providing aerosol descriptions with better and higher spatiotemporal resolution.

Research products and synergistic approaches are paving the way for addressing observational gaps in terms of specific information (e.g., giant particles). In addition to these relevant aspects, there are three main topics which are crucial for the dust observation and impact quantification and management: the dust speciation, data availability, and data traceability. These needs are transversal to many user communities and call for international cooperation and synergy.

For dust model evaluation purposes to the aim of planning action for air quality management, it is fundamental to have observations of dust-only quantities. The review of the existing observations underlines that many new products give the possibility of investigating the presence of mineral dust, but there is currently the need to harmonize the aerosol classification or, whenever this is not possible, to identify translating rules among the wide range of existing classifications. Comparison of typing algorithms is not trivial even when the same kind of observations are used (Voudouri et al. 2019), but such a harmonization process would lead to the integration of the existing dust-only datasets in a coherent and consistent global dataset describing the mineral dust 4D distribution on a global scale. Some initiatives are currently facing this issue, like the International Satellite Aerosol Science Network (AEROSAT). In this context, mineral dust has been considered the first category for facing the typing harmonization process.

NRT and open access availability of data are a common requirement for model assimilation and verification (which is in NRT) and any kind of warning/short-term impact sector, calling for more operational dust-only products from space and ground-based platforms. Dust-related observations are not under any protocols of NRT data exchange under WMO or other UN agencies that would ensure the reliability and efficiency of the operational system. While the timeliness of observations is not a strict requirement for reanalysis and evaluation of the forecast models, spatially/temporally distributed observations, uncertainty characterization of the observations, and homogeneity of the datasets are essential (Benedetti et al. 2018). It is important that observations used in reanalysis and evaluation are well calibrated and accurate and that long time series are provided whenever possible (e.g., Cuevas et al. 2019).

Traceability, quality assurance, and quality control of the data are strictly needed. Metrological approaches can help to improve data quality for in situ and remote sensing techniques, in evaluating sensor characteristics, calibration and measurement uncertainties, and defining data quality and target uncertainties. Full traceability of the data, uncertainty characterization, and harmonization of the data availability in terms of policies, procedures, and interoperability are fundamental for advancing the atmospheric dust field. This can be supported through programs like the WMO-GAW initiative in terms of observational procedures and by the Research Data Alliance, concerning data FAIRness (i.e., Findable, Accessible, Interoperable, and Reusable data).

In synthesis, this paper clearly shows that the development of observational techniques improved the knowledge of mineral dust particles, their global distribution, and their properties. The improved observational capability opened new frontiers and scientific questions to be addressed, increasing the level of requests and needs in terms of observational capabilities. Only international cooperation and synergy can foster the achievement of these objectives of a global, interconnected topic such as atmospheric dust.

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