


Review

Transport of Mineral Dust and Its Impact on Climate

Kerstin Schepanski 

Leibniz Institute for Tropospheric Research (TROPOS), Permoser Str. 15, 04318 Leipzig, Germany;
schepanski@tropos.de

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Abstract: Mineral dust plays a pivotal role in the Earth's system. Dust modulates the global energy budget directly via its interactions with radiation and indirectly via its influence on cloud and precipitation formation processes. Dust is a micro-nutrient and fertilizer for ecosystems due to its mineralogical composition and thus impacts on the global carbon cycle. Hence, dust aerosol is an essential part of weather and climate. Dust suspended in the air is determined by the atmospheric dust cycle: Dust sources and emission processes define the amount of dust entrained into the atmosphere. Atmospheric mixing and circulation carry plumes of dust to remote places. Ultimately, dust particles are removed from the atmosphere by deposition processes such as gravitational settling and rain wash out. During its residence time, dust interacts with and thus modulates the atmosphere resulting into changes such as in surface temperature, wind, clouds, and precipitation rates. There are still uncertainties regarding individual dust interactions and their relevance. Dust modulates key processes that are inevitably influencing the Earth energy budget. Dust transport allows for these interactions and at the same time, the intermittency of dust transport introduces additional fluctuations into a complex and challenging system.

Keywords: mineral dust; dust cycle; dust feedback; dust–climate interaction

1. Introduction

Mineral dust aerosol, a suspension of tiny soil particles in the atmosphere, is widely assumed to be a global player in the Earth's system. Arguments given to support this role are its omnipresence in the Earth system, its ability to modulate the global temperature, and its bio-productivity stimulating characteristics [1,2]. The roles assigned to mineral dust are as follows: Dust particles contribute to the atmospheric aerosol burden not only over desert regions where atmospheric concentrations are highest. Blowing with the winds, dust particles suspended in the air are transported to remote places leading to the second prominent argument supporting the significance of dust in the Earth system: dust impacts. Airborne dust modulates the Earth's radiation budget directly by scattering, absorbing and re-emitting radiation, and indirectly by impacting on atmospheric dynamics and stimulating cloud and precipitation formation processes ultimately altering the hydrological cycle. Third, mineral dust particles deliver micro-nutrients to remote ecosystems where the supply of these micro-nutrients can enhance the bio-productivity of the corresponding ecosystem [3,4] and thus ultimately affect the global carbon cycle. The bio-availability of micro-nutrients and therefore the fertilization efficiency of deposited dust particles is determined by the mineralogical and chemical composition of the particles, which is characterized by the source area but may be altered during transport (e.g., [5]). Close to dust source areas, but also at remote places, airborne dust in the atmospheric boundary layer may negatively impact human health and life style. Road and airport traffic are reduced or closed down during dust events due to low horizontal visibility and resulting hazardous conditions. The reduction of air quality by mineral dust affects respiratory health and is related to increased rates in airborne diseases such as Meningitis or Valley Fever [6–9]. Furthermore, fungus spores, bacteria, pesticides,

and combustion residues are often found in samples of dust aerosol [10–12]. Dust aerosol can also affect economy. The dimming effect of dust on solar radiation reaching the surface reduces the productivity of solar panels and thus the efficiency of solar power plants. Additionally, dust soiling decreases the efficiency of solar energy plants (e.g., [13–15]). Besides natural dust sources like semi-arid and arid areas, soil dust aerosol can be emitted from human induced dust sources such as arable lands ultimately contributing to the local atmospheric dust load [9,16,17]. Modeling studies estimate the fraction of dust emitted from anthropogenically disturbed soil to up to 60% [18].

The atmospheric distribution of mineral dust is strongly controlled by the spatio-temporal distribution of active and thus dust-producing sources. The production of dust and its entrainment into the atmosphere combines meteorology and surface properties. Wind erosion and mobilization of soil particles is a threshold problem, whereby high wind velocities and turbulent fluxes exceeding a local, soil-depending threshold are necessary to mobilize the particles [19]. The amount of dust that can be extracted by wind from the soil, and thus the soil's efficiency to produce dust, varies between different soil types due to different characteristic particle size distributions and particle binding energies [20]. Arid and semi-arid areas are in particular susceptible for wind erosion due to low or absent vegetation cover exposing bare soil to the atmosphere. The knowledge of location and emission flux is a necessary prerequisite for an accurate estimate of dust–atmosphere feedbacks. Dust source activities are highly sensitive to atmospheric and surface conditions, which both are changing in times of changing land use and changing climate conditions. Uncertainties in knowledge of dust source characteristics with regard to their spatio-temporal distribution but also with regard to geomorphology, mineralogy and physico-chemical composition still affect estimates of dust feedbacks by adding uncertainties; the complex role of dust in the climate system is still not understood in all its details.

The contribution of dust emission from human-induced dust sources is still uncertain although progress has been made on understanding the human impact on the dust cycle [18]. Dust emission from these sources is expected to show a strong interannual variability due to the complexity of the interactions between biosphere, geosphere and atmosphere. Estimates of the contribution of anthropogenic dust sources to the global dust load are highly uncertain and are estimated to remain unchanged since nearly a decade [21]. Also, in the event of fire, pyro-convective updrafts inject dust particles from the bare, burned soil into the atmosphere [22]. Dust emission from this process is unquantified to date, although recent in situ observations suggest co-emission of soot and soil dust [23].

Today, the research community has access to a diversity of aerosol products, available at different temporal and spatial resolution depending on instrument (in situ, remote sensing) and platform (ground-based, airborne, spaceborne). In order to obtain information on the vertical distribution and structure of dust suspended in the atmosphere, profiling measurements such as by means of LiDARs are performed. In atmosphere and environmental science, LiDAR instruments operate with lasers at different wavelength to infer particle properties from backscatter characteristics. This allows to distinguish between different types of aerosols such as soot, mineral dust, and sea spray aerosol. Due to the vertical penetration of the laser beam, LiDAR measurements provide information on the vertical distribution of atmospheric aerosols in addition to the aerosol type (e.g., [24,25]).

Satellite data have been used to investigate the atmospheric dust cycle since the mid-1970s when the first satellite observations became available [26]. Since the early stages, the number of satellite observations used for inferring various information on atmospheric dust concentration, dust layer height, and optical properties has significantly increased and so has the diversity in application. Satellite products indicating the presence of dust suspended in the atmosphere are used for source identification (e.g., [27–33]), mapping dust transport pathways (e.g., [34,35]), estimating dust deposition fluxes (e.g., [36,37]), calculating dust impacts on the radiation budget (e.g., [38]), and suggesting dust cloud interactions (e.g., [39]). Satellite data sets are widely used for model validation, however, different measures provided by the satellite instrument and the model simulations can be challenging. To account for this, numerical tool boxes are developed in order to overcome these

differences: Radiative transfer models such as RTTOV (Radiative Transfer for TOVs) are adapted to the needs of models simulating the atmospheric dust cycle allowing for an improved understanding of satellite-based dust products [40] and thus for a more accurate comparison against model simulations.

In situ optical, chemical, mineralogical, and microphysical properties of particles are retrieved from particle sampling instruments. Depending on the measurement device, instruments are operated airborne, shipborne or ground-based. Formenti et al. [41] summarize sampling techniques such as size distribution, composition, surface state, shape, size, and mixing state. Detailed information on dust particle characteristics is necessary to estimate e.g., dust radiative effects and microphysical properties—properties which are most relevant for atmospheric dust feedback on weather and climate. As shown by Caquineau et al. [42], Nickovic et al. [43], and Journet et al. [44] among others, dust mineralogical and optical properties change with source region and are a valuable input in dust models. Implementing these information into dust production models and thus allowing for spatially heterogeneous dust properties results into a variability in dust impacts on radiation, atmospheric dynamics and cloud formation processes [45–47] ultimately highlighting it as an inevitable necessity to accurately estimate dust impact on climate, environment and socio-economy in all its complexity.

To estimate dust emission and deposition fluxes, transport path, residence time, effects on air quality, and the radiative impact of dust particles on the Earth energy budget, dust schemes are implemented in atmosphere circulation models operating at different horizontal scales from global climate models to meso-scale (regional) models to Large Eddy Simulation (LES) models. However, dust models that are used to assess dust atmospheric distributions and its impacts show widely differing results [48]. This points towards shortcomings in boundary data sets and input parameters used for dust emission parameterization.

2. From Source to Sink: The Atmospheric Dust Cycle

The life cycle of mineral dust particles suspended in the atmosphere is commonly introduced as the *atmospheric dust cycle* or the *Aeolian transport system*. Related processes are often referred to as Aeolian processes. It generally consists of three different elements: emission, transport, and deposition. As first element of the atmospheric dust cycle, emission summarizes all processes and conditions during emission. Transport comprises the spread of dust-laden air masses within the atmosphere. This can be at different spatial and temporal scales depending on atmospheric conditions (buoyancy, dispersion, scavenging, aging processes) and particle characteristics (particle size, density, composition, physico-chemical characteristics). The final element, deposition, describes the removal of dust particles from the atmosphere, either active by scavenging and wash out processes, or passive by gravitational settling and turbulence.

2.1. Dust Emission

Dust emission characterizes complex interactions between the wind and the soil surface. It is generally considered to be a threshold problem, which is determined by surface characteristics and surface wind speed [2,19,49,50]. As atmosphere (wind) and surface (barren soil) are acting in concert during dust emission, understanding its controlling mechanism requires knowledge of all relevant surface characteristics (i.e., soil texture, degree of cohesion, crusting, and vegetation cover) and air flow characteristics over the surface. Many measurement studies and wind tunnel experiments under laboratory and outdoor conditions show a non-linear relation between dust uplift described by the number and particle size distribution of uplifted soil particles and the momentum transferred from the atmosphere onto the surface, which is often expressed by the surface wind shear stress [50].

Generally, three different modes of Aeolian transport during dust mobilization, which primarily depend on the particle size, are observed during numerous field studies and laboratory wind tunnel experiments [49,51]. For small particles of less than 70 μm diameter, interparticle cohesive forces are large compared to the aerodynamic forces acting on the particle. With increasing particle diameter, interparticle forces decrease and sand particles with around 100 μm diameter are the first to be

mobilized by the fluid drag of the air flow. Once uplifted, the particle motion follows a ballistic curve as gravity forces are larger than the buoyancy due to turbulent eddies and tear the particle back to the ground. The observed motion is often described as a hopping along the surface and known as saltation [49]. Although the saltating particles do not get into suspension, saltating particles are considered as the essence of dust mobilization. Saltating (hopping) particles are able to mobilize smaller particles due to either the inelastic collision once they hit the ground again, or due to bursting or breaking-up like described by the brittle-fragmentation theory by Kok and Renno [52]. This way, particles of a size class that per se would not be directly entrained into the atmosphere due to strong interparticle cohesive forces, but are very susceptible for turbulent eddy transport within the atmosphere, are mobilized. Particles larger than 500 μm or these which are less exposed to the aerodynamic drag may role along the surface due to the impact of saltating particles.

As confirmed by recent satellite observations, alluvial dust sources contribute a large fraction to the northern African dust sources in particular, but also to the global dust sources in general [29]. Alluvial dust sources (respective alluvial sediments) acting as dust source are of particular interest as these sediments are first very prone to wind erosion and second their erodibility changes over time. The most susceptible particles are removed by wind erosion at first, and the emissivity thus reduces with time. However, the deposition of fresh sediments, e.g., after flash floods, can recharge the dust source as the reservoir of erodible particle is re-filled [53–55]. This forms a link between the hydrological cycle (rain) and dust cycle (erodibility of soil) that possibly partly explains some of the interannual variability of dust emission flux that is observed. This source type is not well represented or even completely disregarded in dust models [56] pointing towards the need for revisiting the representation of different dust source types in dust emission modules.

2.2. Dust Transport

In the air, suspended dust is transported within the atmospheric wind flow. The transport distance strongly depends on the dust residence time in the atmosphere, which is somewhat similar to the dust life time, dust layer altitude, prevailing atmospheric circulation patterns, and buoyancy and gravitational forces. However, particles larger than 70 μm are assumed to deposit within less than one day. Only finest particles with less than 70 μm diameter are kept aloft by atmospheric turbulence and can remain in the atmosphere for up to several weeks and consequently be transported thousands of kilometers downwind [57]. Nevertheless, so called ‘giant’ particles with sizes >100 μm are occasionally found at remote distances (>1000 km) [58–60]. Commonly applied theories explaining removal processes of dust from the atmosphere and thus the possible range of transport distance are currently not able to explain the airborne travel of such large particles in all its details revealing gaps in knowledge. During transport, suspended dust particles interact with solar and terrestrial radiation, ultimately affecting the atmospheric radiation budget by scattering, absorbing and re-emitting radiation. Dust particles may become involved in cloud and precipitation formation processes altering cloud and precipitation properties. Furthermore, photo-chemical and liquid phase chemical reactions on the dust particles’ surface may change the physico-chemical characteristics (e.g., [61]) and thus lead to so called aging of dust particles. Due to aging, also the bio-availability of micro-nutrients provided by the dust particle changes [62].

2.3. Dust Deposition

At some time, depending on the atmospheric conditions during transport, dust particle size and shape, dust particles are removed from the atmosphere either by dry deposition including gravitational settling or wet deposition associated with precipitation and cloud scavenging. Deposited dust particles may impact and interact with the Earth system in several ways: Deposited dust may provide necessary micro-nutrients which enhance and somewhat also controls the bio-productivity (e.g., [3,4]). Layers of dust deposited on plants and leaves may also inhibit photosynthesis due to shadowing and thus reduce bio-productivity. Layers of dust deposits on snow and ice change the

albedo and ice crystal structure altering the melting behavior and snowpack energy balance [63]. Together with the dust particle, microbiological matter may be transported from the source region to deposition environment introducing foreign microbial species originating from the source ecosystem into the remote ecosystems [11,12].

3. Mineral Dust in the Atmosphere

From the atmospheric point of view, the most limiting factors for producing dust plumes are the occurrence of sufficient high surface wind speeds providing the momentum that is inevitably necessary for dust mobilization, and the buoyancy that determines the capacity of the atmosphere to transport and ultimately carry the dust particles. Even an ideal-susceptible dust source will not emit any dust if there is no momentum available that mobilizes the particles and entrain them first into the boundary layer, and then distributes the dust horizontally.

3.1. *Blowing with the Wind: Atmospheric Transport of Mineral Dust*

Dust suspended in the air is carried by turbulence counteracting gravitation and transported by wind. Veritable dust highways—transport pathways that show frequently substantial dust concentrations develop connecting efficiently source regions and deposition areas. All major dust source regions particularly located along the northern and southern tropics (Tropic of Cancer and Tropic of Capricorn) (Figure 1) show dust trails indicating the predominant dust export path which can be identified by enhanced atmospheric dust loadings (Figure 2). As illustrated by fields on dust emission fluxes, dust concentration, and dust deposition rates taken from the ECMWF (European Centre for Medium-Range Weather Forecasts) MACC (Monitoring Atmospheric Composition and Climate) reanalysis data set for 2003–2012, major dust source regions stand out by high annual total dust emission fluxes as well as enhanced atmospheric dust concentrations, here expressed as dust aerosol optical depth (AOD) at 550 nm. Due to general atmospheric circulation and thus prevailing wind direction, dust from most source regions is eventually exported towards the adjacent oceans. Dust is deposited onto the Earth surfaces almost everywhere at least in traces, however, substantial dust deposition is found along the dust transport pathways and downwind major source regions (Figure 3).

Although many data sets reflecting the individual elements of the atmospheric dust cycle exist, for the reason of consistency a model-based reanalysis data set is shown here for illustration: The ECMWF MACC reanalysis data set provides fields on dust emission fluxes, atmospheric dust concentration—here shown as AOD for dust aerosol only, and dust deposition rates separated into the individual contribution by dry deposition, sedimentation, wet deposition due to large-scale precipitation, and wet deposition due to convective precipitation for three size bins ranging between 0.03 and 20 μm (totals over all size bins are shown here) [64]. The data are on a grid with $0.75^\circ \times 0.75^\circ$ grid spacing and a 6-hourly temporal resolution with fields available for 0 UTC, 6 UTC, 12 UTC, and 18 UTC.

The largest and strongest dust source region is located in northern Africa, the Sahara. Not all parts of the Sahara are showing equally high annual emission fluxes and several satellite-based studies have illustrated a strong spatial and temporal variability [29,31,65,66]. One particularly strong emitting source region stands out: The Bodélé depression as key emission source [67]. Embedded in the Harmattan (trade wind) flow, most parts of the emitted dust is transported towards the Atlantic Ocean [2]. Within the Saharan Air Layer (SAL), a distinct layer of enhanced dust concentrations spanning across the tropical Atlantic from the West African coast towards the Caribbean Sea forming at 700–600 hPa during boreal summer months, dust is transported from the North African continent towards the Caribbean Sea within 5–7 days [68,69]. The impact of airborne mineral dust on hurricane formation is still controversially discussed as some studies suggest that airborne mineral dust suppresses tropical cyclone formation [70], whereas others suggest that dusty air masses possibly increase hurricane intensity [71–73]. During boreal winter, the Saharan dust plume is tracking further

southward eventually reaching South America and the Amazon basin [74] where it is assumed to positively stimulate the rainforest ecosystem due to deposition of phosphorous-rich dust particles [75]. Less in amount but still significant and regularly occurring, dust originating from the Sahara and its northern margins is transported towards the Mediterranean and Europe. On average, 13 events per year were observed over the Iberian Peninsula preferably occurring during May to August [76,77], Flentje et al. [78] observed about 5–15 events per year over southern Germany. These events are associated with a mid-latitude disturbance entering the North African continent [79–81]. Dust transport over northern Africa and towards the adjacent oceans is steered by the strength of the Harmattan circulation, the presence and depth of the Saharan heat low, the position of the intertropical discontinuity (ITD) and the occurrence of Mediterranean cold surges (e.g., [82–84]). The strength of the Harmattan winds determine both dust entrainment via the formation of the nocturnal low-level jet (LLJ) [37], and the dust transport across the continent towards the Atlantic [65]. The static stability of the boundary layer and the depth of the daytime convective boundary layer with regard to the nocturnal residual layer are of relevance for the nocturnal transport of dust plumes which ultimately determine the transport height. The Saharan heat low modulates the atmospheric dust burden over northern Africa via the generation of pressure gradients allowing for the formation of nocturnal LLJ that foster dust entrainment [85] and via its impact on the residence time of dust in the air [86]. Mediterranean cold air surges not only are responsible for transport of moisture from the Mediterranean towards the tropics [87], the intrusion of colder air also affects the static stability of the boundary layer and, again, the formation of the nocturnal LLJs, but also the formation of Soudano-Saharan depressions [80]. Dust emission and transport is further associated with the position of the ITD. On its northward side, nocturnal LLJs form due to the evidence of enhanced pressure gradients [37,85,88,89].

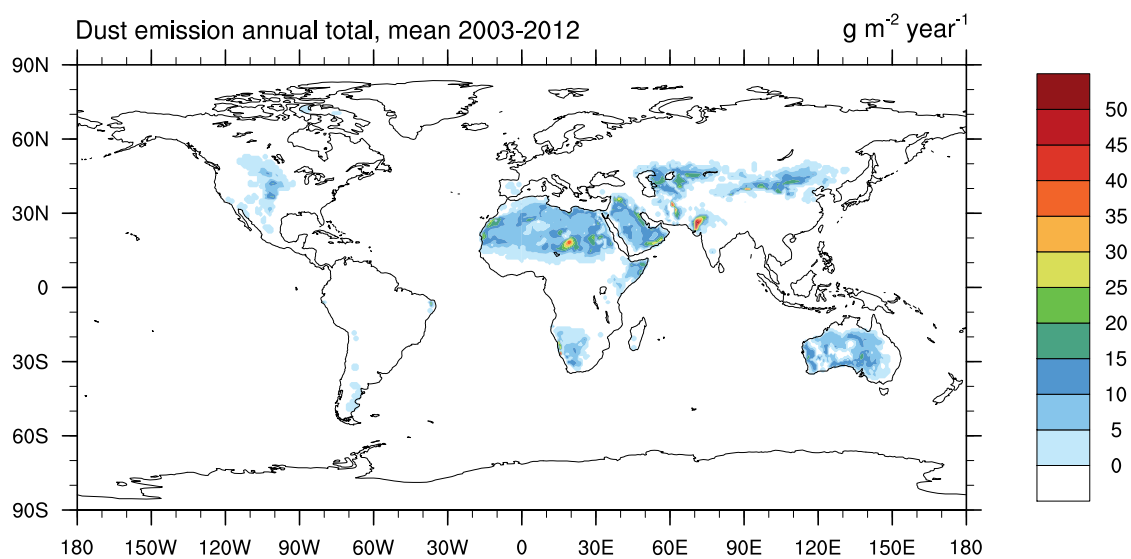


Figure 1. Annual total dust emission fluxes ($\text{g m}^{-2} \text{ year}^{-1}$) averaged over the 10-year period 2003–2012. Data are taken from the ECMWF MACC reanalysis data set at 6-hourly resolution (0 UTC, 6 UTC, 12 UTC, and 18 UTC) and $0.75^\circ \times 0.75^\circ$ grid spacing.

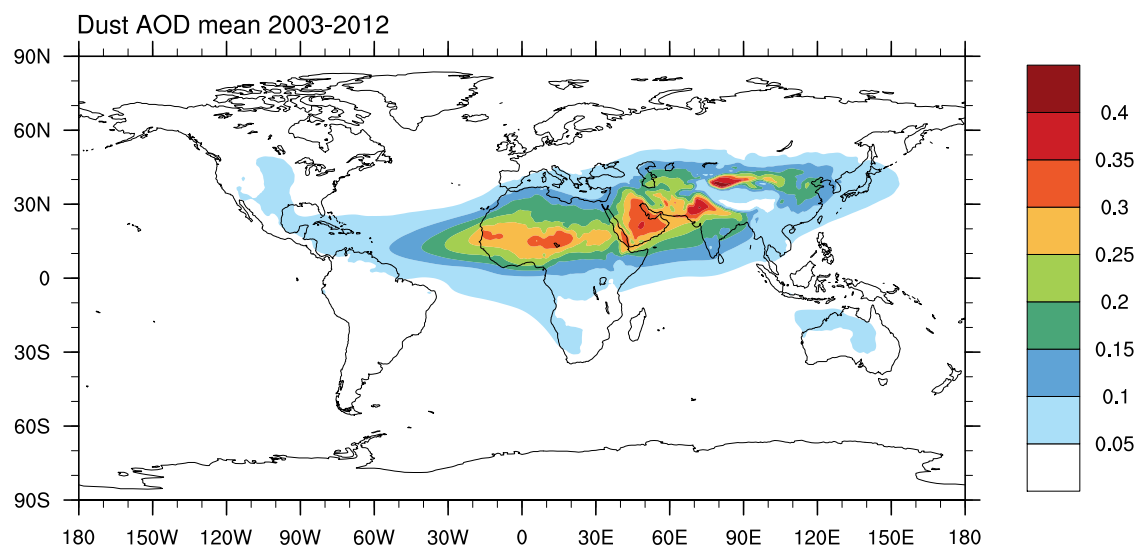


Figure 2. Dust aerosol optical depth (AOD) averaged over the 10-year period 2003-2012. AOD data are taken from the ECMWF MACC reanalysis data set at 6-hourly resolution (0 UTC, 6 UTC, 12 UTC, and 18 UTC) and $0.75^\circ \times 0.75^\circ$ grid spacing.

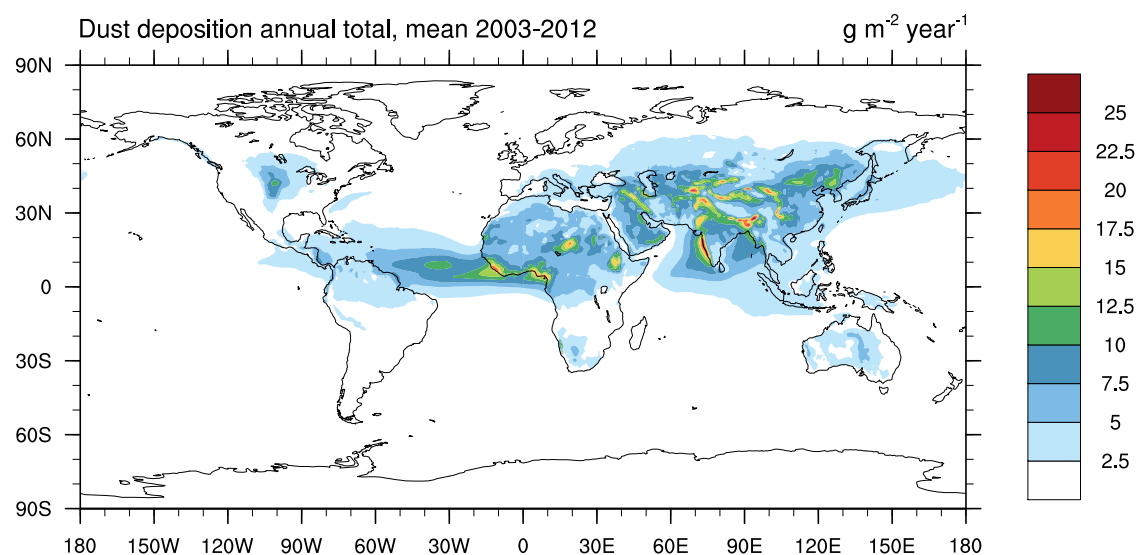


Figure 3. Annual total dust deposition fluxes ($\text{g m}^{-2} \text{ year}^{-1}$) averaged over the 10-year period 2003-2012. Shown deposition rates include dry deposition, sedimentation, wet deposition due to large-scale precipitation and wet deposition due to convective precipitation. Data are taken from the ECMWF MACC reanalysis data set at 6-hourly resolution (0 UTC, 6 UTC, 12 UTC, and 18 UTC) and $0.75^\circ \times 0.75^\circ$ grid spacing.

Along the Tropic of Cancer, the North African desert extends into the Arabian Peninsula, the Middle East and Southwest Asia. Dust from both local and remote sources, in particular North African sources, are contributing to the atmospheric dust burden over this region (e.g., [90,91]). A majority of the dust plumes forming are driven by the Shamal winds (Shamal means northerly in Arabic). During the course of the year, two Shamal seasons occur: Summer Shamal winds associated with the thermal low over Saudi Arabia and Pakistan are blowing somewhat continuously, whereas winter Shamal winds occur as intermittent wind event frequently associated with midlatitude disturbances and their cold fronts [92]. Generally, summertime dust activities in the Middle East are associated with Shamal winds [93], whereas dust plumes transported towards the Indian Ocean are

modulated by the Indian summer monsoon [94]. Occasionally, so called haboobs, dust fronts that are generated by downdrafts from deep moist convective clouds, form and travel over large distances before decaying. In some cases, a sea-breeze circulation can enhance the haboob in terms of strength and life-time [95].

Moving eastward, extensive dust source regions are located in continental Asia. Asian dust, also called 'yellow dust' originates from large desert regions in Kazakhstan, Mongolia, and northern China and is mainly affecting East Asia, predominantly during the spring season when strong winds associated with outbreaks of cold, arctic air masses are pushing southward ([96], and references therein). Dust suspended in the atmosphere is transported eastward towards the metropolitan regions in China causing severe health effects and traffic limitations, and further towards Japan and the Pacific. Eventually, traces of dust reach the northern American continent [97,98].

Since the 21st century, in particular central Asia is subject to environmental changes that foster desertification and dust emission. Due to extensive water usage for the agricultural industry, lake levels are shrinking leaving barren land and increasing dust events. In particular the Aral Sea, once the fourth-largest lake on Earth, has gained much attention during the last decade. Due to the desiccation of the Aral Sea, a new desert, the Aralkum has developed where many dust events originate [99,100].

Asian dust plumes blown off the continent travel as far as towards the North American west coast [97]. In northern America, besides natural desert dust sources such as Mojave, Sonoran, and Chihuahuan deserts, anthropogenically disturbed soils, in particular in the Great Plains region, are identified as dust sources with significant contribution to the North American dust burden and affect on air quality and ultimately human well-being [9,17,101,102].

There are four hot spots in terms of significant dust contribution located in South America: (1) The Bolivian Altiplano and the hyper-arid Atacama Desert in Chile, both enclosed by mountain ranges [29]. (2) A region in west Argentina along the eastern (lee-ward) side of the Andes Mountains (e.g., [103]), and (3) the sandy deserts and semi-arid regions in Patagonia (e.g., [104]). The fourth region is located in tropical Brasilia, an area extensively used for agriculture. Most amounts of the emitted dust is transported towards the Atlantic and southern Ocean. Dust emitted in the Atacama and the Bolivian Altiplano desert is generally at a low level and transport off the source region is somewhat limited by the surrounding mountain ranges [29].

In southern Africa, three dust source regions predominantly contribute to the dust burden: The coastal river beds and pans of the Namibian desert, the Etosha Basin and the Makgadikgadi Pan [32]. Berg-winds, strong winds associated with coastal low pressure systems, accelerate while flowing downhill from the inland plateau across the Escarpment towards the Atlantic. On their way, the strong winds swirl up dust, which forms stripy dust plumes blowing onto the southern Atlantic. These coastal low pressure systems occur in particular during the austral late winter and early spring. Despite the dust transport towards the southern Atlantic, dust particles are also leaving southern Africa towards the Indian Ocean. Embedded in a haze layer, an anticyclonic flow transports aerosol from the continent in south-easterly direction [105].

Dust plumes over Australia originate from arid desert regions in the inner part of the continent such as the dried lake beds of Lake Eyre [106] and are transported offshore towards the northwest and southeast by wind systems associated with the eastward passage of non-precipitating cold fronts [107]. The dust season peaks in austral spring and summer for central, northeastern and eastern Australia, and austral summer and autumn for southeast, southern and western coastal Australia [108]. The dust storm season is driven by the length of the dry season and terminates with the on-set of the rainy season. During summer, strong anticyclones located over the Great Australian Bight inhibit fronts from migrating inland [108].

Although globally a minor contribution to the atmospheric dust burden, emission from dust sources located at high latitudes and in cold climates may be of importance for the local ecosystem, in particular in the view that high-latitude ecosystems are highly sensitive to disturbances and changes [109,110]. Typical high latitude dust sources are glacial outwash planes, temporally flooded

river banks, and sandurs [111,112]. There, the vegetation cover is low and water regularly deposits layers of fresh sediments. Prominent dust sources at high latitudes are the Copper River in Alaska [113], West-Greenland [111], and Iceland [114] at the northern hemisphere, and Patagonia [104] and New Zealand [115] at the southern hemisphere. Recent studies have shown the sensitivity of the marine eco-system towards nutrient influx via dust deposition. Shoenfelt et al. [116] recently proposed that nutrients contained in dust originating from glacial sources at high latitudes show higher levels of bioavailability and thus a stronger potential to influence on the oceans bioproductivity and thus the global carbon cycle. Strong interannual variability in dust storm occurrence and thus dust deposition fluxes lead to significant interannual variability in iron deposition fluxes as shown by Schroth et al. [117] for the Gulf of Alaska.

3.2. Interannual Variability

Dust source activity and dust transport pathways are modulated and superimposed by variations in atmospheric circulation patterns. The Saharan dust plume, the most conspicuous dust plume contrasting against the Atlantic Ocean when studying satellite images, is modulated by the position and strength of the Azores high, which is reflected by the North Atlantic Ocean (NAO) index [118,119]. The North African Dipole index as introduced by Rodríguez et al. [82] additionally reflects the meridional pressure gradient across North Africa, which is also stimulated by the Saharan heat low and the West African Monsoon circulation ultimately determining the dust export rates towards the tropical North Atlantic (e.g., [82,84]). Doherty et al. [120] further identifies pressure fluctuation of the Hawaiian high to modulate the Saharan dust transport across the Atlantic towards the Caribbean.

Several recent studies have investigated the atmospheric controls on increased dustiness over North America, in particular southwestern US (e.g., [9,17,101,121,122]). All studies illustrate the relevance of the Pacific Sea Surface Temperature (SST) and highlight strong correlations between atmospheric dust concentrations respective levels of dustiness and the phase of the Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO). Dustiness, in particular over the southwest, is correlated with the PDO index which in its negative phase leads to drier, windier and less vegetated conditions [101,121]. Consequently, the SST of the Pacific and North Atlantic have a strong modulating impact on North America's atmospheric dust burden [122]. Persistent and multi-annual droughts are correlated with an increase in dustiness, in particular over the southwestern US. Severe events are well remembered as 'dust bowl' years, when large regions were affected by drought-related dustiness, health impacts and economic losses in particular in the agricultural sector [16].

ENSO not only results into dust-favoring conditions in the US. Enhanced frequencies of dust events in Argentina are related to drier conditions related to El Niño [103] and dust concentrations over the Indian Ocean linked to dust emission over the Indo-Iranian region are enhanced following La Niña [123]. For southern Africa, Bryant et al. [124] illustrates the role of changes in precipitation rates linked to ENSO and Indian Ocean SSTs for dust emissions, with enhanced rainfall associated with La Niña. Rainfall anomalies over Australia are also modulated by ENSO and the PDO ultimately resulting into variabilities in dust emission [125,126]. For the Middle East, Yu et al. [93] found an impact of ENSO on the onset and termination of the summer Shamal season ultimately modulating dust source activity and transport pathways. A superposition of ENSO and PDO modes is suggested to result in a long-term drying and thus prolonged drought conditions which foster dust activity over the Middle East and Arabian Peninsula [75,127]. The peak season for Asian dust emission and transport is during boreal spring, where Arctic cold fronts drive strong dust fronts towards the Pacific. The Arctic Oscillation reflecting the position and strength of the Arctic high is explaining large parts of the dust storm variability in Asia [128]. The trans-Pacific transport of dust is modulated by ENSO and PDO with El Niño years being associated with a northward shift of the transport route ([121], and references therein).

3.3. Dust Feedbacks and Impacts

Dust aerosols are a significant uncertainty in estimating the Earth's energy budget in a changing climate [21]. The impact of dust on different processes relevant for weather and climate is manifold: Dust aerosols participate in cloud formation processes and thus stimulate the hydrological cycle. They furthermore modulate the atmospheric radiation budget by scattering, absorbing and re-emitting radiation. Indirectly, changes in radiation budget alter heating rates and thus atmospheric dynamics [129,130]. Detailed knowledge of dust optical and physico-chemical properties are inevitable for understanding dust direct impact via radiation and dust indirect impact via cloud processes feedbacks on the atmospheric system.

Given that dust's impact on the Earth system is via the energy budget, and the processes determining these impacts occur while dust is suspended in the atmosphere, dust transport is an essential component. The impact may be magnified by the residence time of dust plumes in the atmosphere, which is also linked to the geographic distance of the transport pathway.

3.3.1. Radiation

Dust particles scatter, absorb and re-emit radiation at different wavelength of the spectrum depending on their optical properties including size, shape and composition. These properties vary for different source regions. Size distribution changes with the travelled distance as larger particles sediment quicker than smaller particles due to gravitation. Furthermore, the physico-chemical properties may change during transport due to aging processes such as the particle's participation in cloud particle formation processes or chemical reactions with other aerosols and atmospheric trace gases.

The dust particle size distribution is the most relevant property when estimating the impact of dust on the Earth's energy budget. Kok et al. [131] suggest that dust in the atmosphere is substantially coarser than represented in current global climate models, which in turn, will result into an enhanced positive radiative forcing and an increasing atmospheric dust loading. Consequently, the global dust direct radiative effect is likely to be less cooling than currently assumed, which includes the possibility that dust causes a net warming of the planet. The transport of larger dust particles through the atmosphere over long distance is also illustrated by airborne dust samples [59] and marine dust traps along a transect across the Atlantic [60].

Direct radiative forcing of dust, defined as the change in radiation flux due to the presence of dust particles suspended in the atmosphere, modulates the atmospheric energy budget with consequences on parameters such as temperature, pressure and wind (e.g., [132,133]). Due to the ability to absorb and re-emit radiation, dust plumes drifting through the atmosphere may act as a so-called elevated heat source. Thereby, a dust layer may change the vertical temperature gradient and thus the static stability of the atmospheric column. Changes in static stability result vertically into adapting mixing rates e.g., affecting the downward mixing of energy such as momentum provided by winds, and horizontally on thermal wind balances causing horizontally changing pressure gradients, which alters the horizontal wind [134]. Effects of dust via radiative forcing on atmospheric measures, such as wind, affect in turn the uplift of dust itself consequently somewhat regulating the local dust burden over source regions.

3.3.2. Clouds

Dust particles may alter cloud microphysical and macrophysical (i.e., liquid water path, cloud fractional coverage) properties [39]. Dust aerosols can become involved in cloud particle formation processes thus influencing cloud properties such as particle size distribution, cloud thickness, liquid water path, spatial extent, life-time, precipitation. The aerosol-cloud feedbacks and the buffered response of cloud properties resulting from this still poses a grand challenge in understanding the sign and magnitude of aerosol impacts on clouds in particular and the hydrological cycle and the Earth's energy budget in general [135].

The stimulating impact of aerosols on clouds is diverse. Twomey [136] describes the relation between cloud condensation nuclei (CCN) concentration and cloud droplet size distribution for low-level stratus clouds. The study compares polluted to pristine clouds, whereby in polluted clouds the cloud droplet concentration increases with increasing CCN concentrations compared to pristine clouds. At the same time, the cloud droplet size distribution shifts towards smaller droplets. Consequently, both cloud shortwave albedo and longwave emissivity increase. Due to the increased number of smaller cloud particles at the cost of larger cloud droplets, the chance for the formation of precipitable cloud drops decreases. Furthermore, the onset of freezing will be delayed and the riming efficiency will be decreased. An increased cloud lifetime and vertical extent of clouds associated with enhanced aerosol concentrations shows an important feedback on the hydrological cycle.

Mineral dust particles are found to be suitable acting as CCN but also as ice nuclei (IN) (e.g., [137]). Thereby, the mineralogical composition of soil particles acting as CCN respective IN, the particles shape and surface structure, and their microphysical properties are relevant for its successful action in cloud formation processes. The role of mineral dust particles in cloud formation processes is observed during several measurement campaigns (e.g., [138]) and confirmed by laboratory studies (e.g., [139]). Modeling studies implementing observed dust-cloud interaction processes provide insights into regional and global implications as well as they enable the community to assess the relevance of dust-cloud interactions for the atmospheric energy budget, the hydrological cycle and thus the Earth climate. Besides its relevance for climate, simulations by numerical models that consider dust-cloud interactions show improved performances and match better with observation data (e.g., [140]). Due to its abundance, mineral dust is currently assumed to be one of the most important IN types in the atmosphere ultimately stimulating the formation of cirrus clouds which have a strong influence on the global energy budget as they scatter the incoming radiation back to space but also trap the outgoing terrestrial radiation [141]. Dust cloud interaction processes and their relevance for the Earth system are part of ongoing research and the interpretation and quantification of results are still challenging [21].

3.4. Processing: Dust Aging

During transport, dust particles are exposed to several environmental influences such as, obviously, radiation and humidity, but also other chemical compounds. These aerosols (solid, liquid or gas) may be emitted through natural processes such as bio-productivity, wild fires or sea spray, and industrial production processes. These plumes of different types of aerosols may mix internally or override each other in stable layers, clearly separated from each other. In case of mixing, coatings may be deposited on dust particles changing their microphysical properties and ability to act as a condensation or ice nuclei (e.g., [142–144]). Also the solubility and thus the bioavailability of micro-nutrients carried within the mineral dust particles can be enhanced after chemical dust processing (e.g., [62,145]), which also effects the occurrence and extent of algae blooms.

4. Implications for Climate

Dust transport ranges over a variety of different scales. Small-scale turbulent processes keep the dust aerosols aloft, air movements are responsible for the transport of dust plumes off the source area towards remote regions. Dust suspended in the air and transported by wind systems of various scale is balanced by (1) the emission flux replenishing the atmospheric reservoir of floating mineral dust particles and (2) by the deposition rates, the removal of dust from the atmosphere so to say. In a nutshell, the atmospheric concentration of mineral dust is determined by the emission flux, the dispersion, and the deposition. Changes in at least one of these determinants will result into changes in atmospheric concentration and consequently also in the extent of dust feedback processes.

Dust transport, the connecting part between dust emission and deposition, however, adds the spatial dimension to the atmospheric dust cycle, and with it the temporal dimension as dust transport over long distances involves a longer permanence than over short distances. This way, also the chance that dust feedbacks occur are increasing and with it the impact of dust in the climate system in general.

The atmospheric dust concentration is a key-measure for assessing dust impacts as most feedbacks such as on radiation, cloud formation, and fertilization scales with the atmospheric dust loading and so does the dust's impact on the Earth energy budget. Furthermore, dust concentrations reflecting dust transport are a common measure for comparing between numerical model simulations and remote sensing and in situ measurements.

Mineral dust plays a key role in the Earth systems, however, there are still uncertainties regarding specific dust interaction processes and their relevance. Dust aerosol modulates and stimulates key processes that are inevitably influencing the Earth energy budget and thus its thermostat. Dust transport contributes to these interactions as it ultimately ensures for the presence of dust particles in the atmosphere. At the same time, the intermittency of dust transport introduces additional fluctuations into a complex and challenging system.

5. Future Research

Mineral dust is a dominant constituent of the atmospheric aerosol burden. Nevertheless, dust aerosol is one of the uncertainties the estimating aerosol climate feedbacks and the global energy budget in general. Whereas the emission of industrial aerosols becomes more and more controlled and regulated by political efforts [146], the emission of natural aerosols such as mineral dust is highly susceptible to modifications due to climate change thus showing a high potential for important feedbacks on the climate system [1] and vice versa [147]. Eventually, as anthropogenic aerosol emissions are expected to decline, this will lead to an increased contribution by natural aerosols to the global aerosol burden.

Emerging from the overarching question on the role of mineral dust in the Earth system including dust feedbacks on the climate system ultimately contributing to current uncertainties in estimating the global energy budget, major research questions are on the dust cycle including controlling processes and resulting impacts such as the identification of 'first order' dust processes stimulating the climate system. In order to achieve this and ultimately in order to reduce the uncertainties in climate projections, new findings on the dust cycle including source characteristics, emission, transport, deposition, and dust related processes need to be implemented in ongoing model development. Ideally, findings across various research disciplines working on mineral dust need to exchange knowledge. One example on this is the update of boundary data by using new approaches for describing dust source characteristics in order to improve the representation of dust emission fluxes in dust production models. Elaborating on the representation of the dust cycle in numerical models, new strategies on validating model output fields against observation data (remote sensing, in situ) will be developed in order to better match the information content of the data sets to be compared.

Besides efforts on ultimately reducing the uncertainty in Earth system models, dust impacts on human wellbeing and economy are emerging topics. Evidence is shown that dust particles suspended in near-surface air masses have a negative effect on human health. However, the actual process on how dust aerosols that were inhaled are acting on the immune system ultimately promoting diseases is still not known in all its details, but part of recently upcoming interdisciplinary research efforts.

In a nutshell, future research on dust and involving dust will be divers, innovative and relevant for some of the major question concerning the society. Divers regarding individual processes and topics addresses. Innovative regarding involved novel approaches and cross-cutting hypotheses. Relevant because protecting the environment, understanding and mitigation of climate change are the major challenges society faces in the 21st century.

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