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EDITED BY
Hong Liao,
Nanjing University of Information Science and Technology, China

REVIEWED BY
Jean-Baptiste Renard,
UMR7328 Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), France
Jingyi Chen,
Pacific Northwest National Laboratory (DOE), United States

*CORRESPONDENCE
Sagar P. Parajuli,
psagar@utexas.edu

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Editorial: Atmospheric dust: How it affects climate, environment and life on Earth?

Sagar P. Parajuli[1]*, Qinjian Jin[2] and Diana Francis[3]

[1]King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, [2]The University of Kansas, Lawrence, KS, United States, [3]Khalifa University, Abu Dhabi, United Arab Emirates

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Editorial on the Research Topic
Atmospheric dust: How it affects climate, environment and life on Earth?

1 Introduction

Mineral dust particles, which are mainly emitted from deserts and agricultural areas (Shao et al., 2011; Ginoux et al., 2012), are the second largest constituents of atmospheric aerosols by mass. They block the sunlight by scattering and absorption, which in turn affects the Earth's physical and biological processes (e.g., Mahowald et al., 2009; Bangalath and Stenchikov, 2015; Parajuli et al., 2022). Dust aerosols directly affect air quality (e.g., Ukhov et al., 2020), provide nutrients (e.g., phosphorous, iron) to marine and terrestrial ecosystems (e.g., Kellogg and Griffin, 2006), darken snow and ice surface thus have impact on cryosphere (Francis et al., 2018; Francis et al., 2022), and can also change rainfall distribution by modifying circulation patterns and cloud properties (Shao et al., 2011; Choobari et al., 2014; Jin et al., 2017; Francis et al., 2021a; Parajuli et al., 2022). Dust bowls of the 1930s, caused by severe droughts coupled with poor agricultural practices over the American and Canadian prairies made extensive crop damage, affected daily lives, and contributed to the economic downturn during the Great Depression (Bolles et al., 2017). Prevailing air pollution in populated cities around the world clearly highlights the impact of these tiny atmospheric particles on human health. In this context, in this paper, we highlight some known challenges of dust observation and modeling, in an attempt to identify and guide future research direction.

1.1 Dust emissions

Our understanding of atmospheric aerosols has grown significantly in terms of their types, physical properties, chemical composition, radiative effects, and hygroscopic properties during the past decades due to advances in observational techniques and model development. Global and regional weather/climate models are used to simulate the emission of dust and its interactions with the climate (Chen et al., 2014; Kok et al., 2014; Jin et al., 2015; Francis et al., 2021a; Singh et al., 2021; Parajuli et al., 2022). However, the large spatiotemporal heterogeneity of dust sources, from giant sand dunes to small ridge and furrows of the agricultural field, from short-lived dust devils for several minutes to global dust transport for several weeks (Uno et al., 2009; Francis et al., 2020), makes it extremely challenging to represent the dust cycle (emission, transport, and deposition) in climate models. Recent studies show that most global climate models used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) fail to reproduce the key aspects of the dust cycle when compared to satellite and ground-based observations (Evan et al., 2014; Singh et al., 2018), partially due to poor simulation of circulations. Since these models are increasingly being used for conducting historical as well as future climate simulations, there is a pressing need for improving the overall representation of dust cycle and dust-climate interactions in the models. Figure 1 summarizes our present understanding of the multi-faceted aspects of dust-climate interactions.

One of the most pressing challenges in dust modeling is to represent anthropogenic dust sources (Ginoux et al., 2012; Webb and Pierre, 2018). Anthroposphere is a changing space and thus it is challenging to identify and represent new dust sources that keep emerging with urbanization, desertification (Jin et al., 2017), and changes in agricultural practices. For example, the Tigris-Euphrates region is one of the most active anthropogenic dust sources, which continues to expand in its strength because of increased or bad agricultural practices (Parajuli et al., 2019). It will not be surprising if it becomes the center of a modern “Dust Bowl” in the future under a prolonged drought scenario because it shares many similarities with the high plains of the United States. Such a disaster will be very costly in terms of the regional economy, ecology, and air quality. Therefore, given their regional effects, regional cooperation among all nations is essential to avoid such occurrences in the future.

One of the main uncertainties of dust–climate interactions comes from the poor representation of dust sources, emissions,

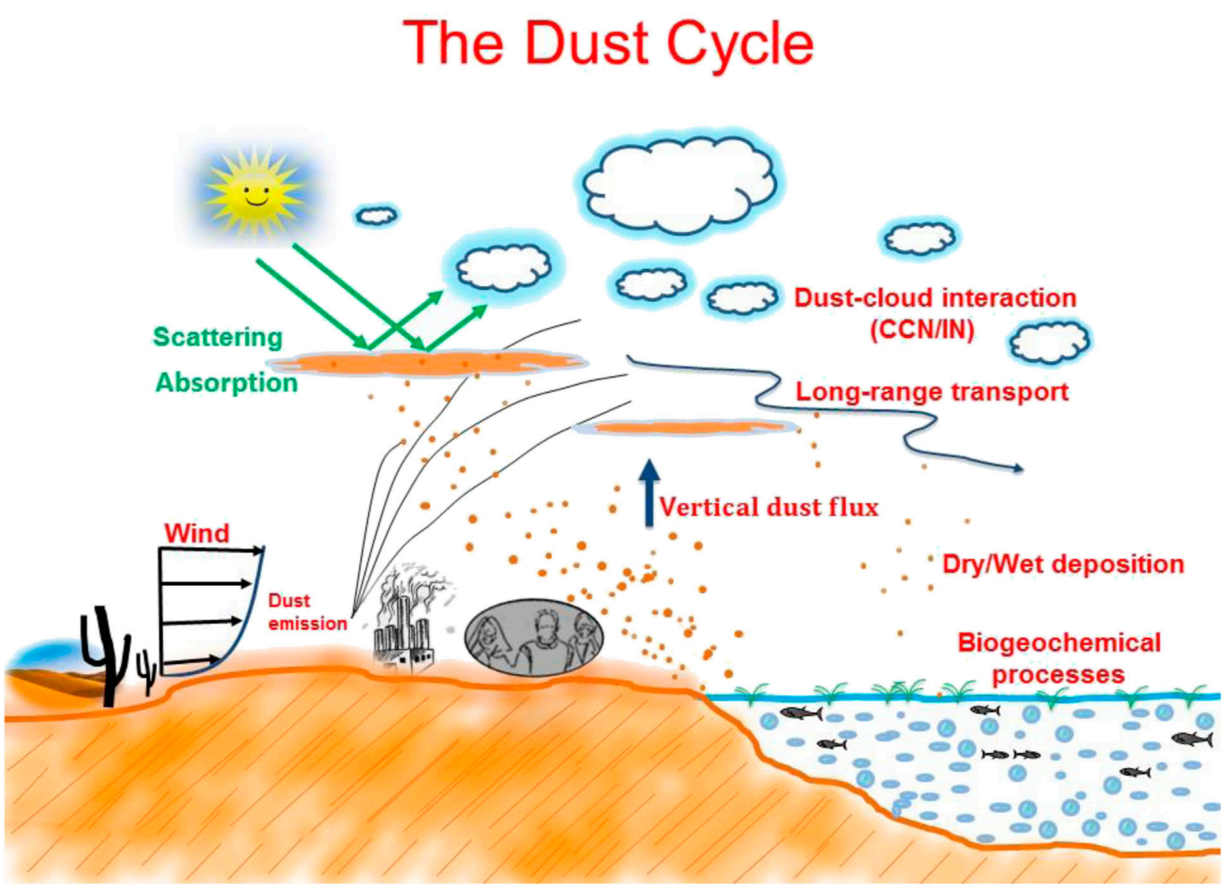

FIGURE 1
The dust cycle and its impacts.

and mineral components. Dust parameterizations currently used in most dust modeling schemes were either derived from wind-tunnel or field experiments, which produce unrealistic emission fluxes in their global application because of their scale dependency. Unfortunately, there has been no solid progress in terms of improving dust emission fluxes given the large diversity of natural as well as anthropogenic dust sources. A few notable attempts have emerged recently in this regard (e.g., Chappell et al., 2021; Kok et al., 2021; Leung et al., 2022) but reasonable representation of dust fluxes remains a big challenge in climate models.

1.2 Dust/aerosol optical properties

Dust optical depth (DOD) is a measure of how much solar radiation is blocked by dust aerosols within the entire atmospheric column. In most dust modules used in climate models, dust emission fluxes are calculated using simple equations, originally derived from wind tunnel or field experiments (Marticorena and Bergametti, 1995). These equations calculate how much dust is emitted into the atmosphere (vertical flux of dust) mainly as a function of surface winds, soil particle size distribution, soil moisture, soil erodibility, and clay content. When such fine-scale parameterizations are adapted for calculating grid-scale emissions in global/regional models, they must be constrained using appropriate observations. Otherwise, the calculated dust fluxes will not be realistic. This is one reason why different dust models currently in use give a range of global dust emission estimates, from 500 to 5000 Tg/year (Zender et al., 2004; Huneeus et al., 2011).

To deal with the issue discussed above, it is a usual practice to constrain dust emissions in the models against some ground-based observations or satellite retrievals (Zhao et al., 2010; Parajuli et al., 2019), by utilizing a tuning parameter obtained iteratively until the desired match is obtained between predicted and observed AOD (Aerosol Optical Depth). This tuning parameter is highly sensitive to spatial and temporal resolution; therefore, it is important to determine this tuning parameter for each model set-up independently rather than using the prescribed values in the default model configuration. Inadequately tuned models, when used for conducting historic, present or future climate simulations, can yield unrealistic AODs. Consequently, the subsequent processes involving dust–radiation interactions as well as dust–cloud interactions can be ill-simulated, which in turn can misrepresent the impacts of dust aerosols on climate. Another important issue is that while tuning the dust model to get the desired AOD, we are essentially assuming that the loadings of other aerosol species are well simulated by the model or they are less important. While it is true that dust is the major contributor to AOD in desert areas (Parajuli et al., 2019; Francis et al., 2021b), it may not be the case in some regions where sea salt, biomass burning, organic, and other anthropogenic aerosols may contribute significantly to the total AOD. Although it is possible to get the proportion of DOD to total AOD from satellite retrievals, e.g., CALIOP (Winker et al., 2013), this data suffers from coarse resolution, incomplete sampling, cloud contamination, and an assumption of a constant dust LIDAR ratio. A more effective method to determine the contribution of different aerosol types to total AOD is yet to be invented and is a key topic for further research.

Recent field and laboratory measurements show that the dust refractive index in the longwave band varies regionally, particularly the imaginary part (Di Biagio et al., 2017; Kok et al., 2021). Another large uncertainty regarding dust optical depth is the mineral components of dust aerosols, which determines both physical and chemical properties of dust aerosols, in particular the absorption of solar radiation by dust aerosols. Observational data demonstrate large spatial variations in dust mineral components (e.g., iron oxides) on a global scale (Perlwitz et al., 2015; Di Biagio et al., 2019). However, most of the current climate models assume that all dust particles in the atmosphere have the same mineral components and thus utilize a globally-constant value for the imaginary part of the dust refractive index, which is determined by dust mineral components (Sand et al., 2021). Therefore, in future model development, dust aerosols should be treated as various mineral components to better estimate dust total optical depth as well as dust absorptive optical depth, the latter of which plays a significant role in the dust–climate interactions (Green et al., 2020; Li et al., 2021).

1.3 Particle size distribution

Dust particle size distributions (PSD) shows what range of sizes of dust particles are there in the atmosphere. PSDs of atmospheric aerosols determine the amount of light scattered or heat absorbed as well as the formation of cloud condensation nuclei (CCN) or Ice Nuclei (IN), which ultimately govern the aerosol-cloud interactions and associated rainfall processes (Mahowald et al., 2014). Therefore, it is important to ensure that the predicted PSD is realistic in the model. Although the availability of PSD observations is limited, size distributions obtained by inversion from the AERONET network are sufficient to obtain a reasonable PSD (Parajuli et al., 2020). AERONET is a global network of more than 400 stations retrieving key aerosol properties including optical depth and size distributions (Holben et al., 1998). However, near major dust source regions, these observations are scarce (Francis et al., 2019) which induces uncertainties in regional and global models. Adebiyi and Kok. (2020) have shown that most models miss the coarse dust particles near emission regions due to a fast deposition of large particles. This induces a bias in dust aerosol interaction with the longwave radiation where large particles are associated with a warming effect (Francis et al., 2021a; Francis et al., 2022).

1.4 Aerosol vertical distribution

Dust vertical distribution is another important aspect that is often overlooked while conducting global/regional climate simulations (Parajuli et al., 2020), which indicates how much dust load is present at different altitudes in the atmosphere. The vertical distribution of aerosols affects physical processes near the surface as well as in the upper atmosphere. For example, if the vertical distribution of aerosol concentration is not realistic, the model will show unrealistic surface PM10/PM2.5 even if the total columnar AOD is right. This could lead to serious consequences in air quality applications. Similarly, if the aerosol concentrations are not realistic in the upper atmosphere, CCN/IN number concentrations will not be accurate and consequently, cloud properties such as cloud depths, cloud heights, and mixing ratios of hydrometeors (e.g., rain, graupel, snow, and ice) will be affected.

In the above context, Lidar data, which are available from several ground-based sites, aircraft, and satellite platforms across the globe (Winker et al., 1996; Welton et al., 2000), can be instrumental in constraining the vertical distribution of aerosols in the models. The Micro-Pulse Lidar Network (MPLNET), maintained by the NASA Goddard Space Flight Center (GSFC), is a network of MPL lidars and a huge volume of data on vertical profile are available across the globe (Welton et al., 2002). Other coordinated lidar networks include the European Aerosol Research Lidar Network EARLINET (Pappalardo et al., 2014), German Aerosol Lidar Network (Bosenberg, 2001), the Latin American Lidar Network LALINET (Guerrero-Rascado et al., 2016), the Asian dust and aerosol lidar observation network AD-Net (Shimizu et al., 2016), and the Commonwealth of Independent States Lidar Network CIS-LiNet (Chaikovsky et al., 2006). These data can be used to verify or constrain the model-predicted aerosol vertical distributions.

1.5 Dust direct, semi-direct, and indirect effects

When dust scatters or absorbs shortwave radiation, it affects the radiation budget at Earth's surface and in the atmosphere thus directly changing Earth's surface and atmospheric temperature, respectively. Such temperature change brings about a wide range of consequences, from local circulation changes to changes in convective activity. The effects of aerosols on climate are generally classified into three categories, which are direct, semi-direct, and indirect effects (Lohmann and Feichter, 2001; Forkel et al., 2012). Aerosol directly affects Earth's radiative budget by scattering and absorbing shortwave radiation, which is generally known as the "direct aerosol effect." Dust effects on radiation in turn lead to changes in temperature, wind speed, relative humidity, and atmospheric stability. These consequential effects are called aerosol "semi-direct effects" (Hansen et al., 1997). Additionally, aerosols also affect Earth's climate through clouds as they interact with clouds in multiple ways. These effects that occur through clouds are classified as indirect effects (Twomey, 1991). The indirect effects are further classified into two categories. Aerosols form cloud condensation nuclei (CCN) or ice nuclei (IN) (Stull, 2000) and thus change the cloud optical properties including cloud albedo—the "first indirect effect" (Kravitz et al., 2014). The subsequent changes in other cloud properties including cloud cover, cloud lifetime, and rainfall are called the "second indirect effect" (Lohmann and Feichter, 2001).

Several studies have shown that dust particles, especially near source regions, induce a warming effect at the surface (Francis et al., 2020; Francis et al., 2021a; Francis et al., 2021b) which is not well represented in regional models (Francis et al., 2021a; Kok et al., 2021). This misrepresentation may be due to the fact that models tend to deposit large particles faster than in reality (Kok et al., 2021). Therefore, dust size particles, their deposition, and interaction in the longwave band need to be revisited in current models.

Atmospheric dust aerosols are also known to affect regional atmospheric circulation by modifying the radiative balance both at the surface and throughout the atmosphere, i.e., the semi-direct effects. To date, large uncertainties remain with regard to the impact of aerosols on atmospheric stability, convection and wind patterns (Francis et al., 2021a; Francis et al., 2021b). Additionally, the impacts of dust on the radiative budget, and hence on the circulation, can differ from over land to over water due to the difference in surface albedo between the two locations. The spatio-temporal heterogeneity in dust semi-direct effect makes it even more complex to account for in climate models.

Dust particles can further affect the rainfall patterns through various direct and indirect pathways (Koren et al., 2005; Jin et al., 2015; Parajuli et al., 2022). Changes in rainfall patterns can have broader and long-term consequences because the entire biosphere directly depends upon rainfall for its survival. Unequal distribution of rainfall can affect the frequency and intensity of floods and droughts and affect the distribution of regional water resources. Changes in the prevailing monsoon system and rainfall pattern can affect agricultural production, limit access to drinking water supply, and affect daily life activities.

Dust aerosols emitted from the Middle East have been shown to strengthen the Indian summer monsoonal circulations and thus precipitation (Jin et al., 2014; Vinoj et al., 2014; Jin et al., 2015; Jin et al., 2016). Dust aerosols accumulated over the Arabian Sea can induce a strong warming effect in the middle troposphere, which increases the meridional thermal contrast and thus enhances the southwest monsoon flow, pumping more moisture from the northern Indian Ocean and the Arabian Sea to the Indian subcontinent and ultimately resulting in more precipitation. Beyond Asia, similar dust–monsoon interactions are also identified in North Africa (Zhao et al., 2011) and North America (Zhao et al., 2012).

The direct and indirect effects of dust on rainfall was quantified recently by Parajuli et al. (2022). The study which used WRF-Chem simulations over the Red Sea coastal region showed different responses of dust on rainfall for extreme and normal rain events. Dust enhanced net rainfall for extreme events (~6%) but suppressed (~−1%) for normal rain events. For extreme rainfall events, the net effect was primarily driven by indirect effects, which enhanced rainfall by about +4.6%. This is because extreme rain events are usually caused by synoptic features and the high dust concentration facilitates raindrops to grow in the presence of sufficient moisture. For normal rainfall events, the net effect was governed by direct effects, which suppressed rainfall by about −5.8%. The result was suppression because the dust's direct effect depends upon the local circulation, the sea breezes in their case. Dust scatters shortwave radiation, cools the land surface and thus weakens the sea breeze circulation, which brings more moisture to the land ultimately suppressing the rainfall.

Considering the fact that aerosols are essential for rain formations in warm clouds, these effects are perhaps smaller than what happens in the real world. The small effects observed are in part due to the modeling challenges. It is difficult or even impossible to know the actual effect of dust on rainfall in a modeling framework because we do not know which backgrounds aerosols precede in seeding the clouds in the real world.

2 The way forward

In summary, more *in-situ* measurements and remote sensing observations from satellites are needed to better understand the dust effect on climate. Dust parameterizations should be improved based on currently available ground-based and satellite observations. High-resolution simulations accounting for direct and indirect effects of dust can unravel the various physical mechanisms of dust-climate interactions. We urge the scientific community to pay attention to the above details in global/regional climate models and make attempts to improve them so that the models can realistically represent the effect of dust on climate in past, present or future climate simulations. Although we illustrated the above aspects with regards to dust, they are equally important for all other aerosol types, including natural (e.g., sea salt, biogenic emissions) and anthropogenic (e.g., sulfate, black and organic carbon).

Collection summary

In this Research Topic, we have presented articles focusing on the effect of dust on health, climate, as well as ways to improve dust-forecasting capability with data assimilation. An article by Wang et al. showed how dust affects Indian Summer Monsoon both in the short-term (fast response) and long-term (slow response), through its effect on the atmosphere and ocean, respectively. Plocoste et al. presented a novel statistical technique to calculate PM10 thresholds using aerosol concentration in the areas where mineral dust contributes significantly to total atmospheric aerosol loading. Huo et al. highlighted that the presence of sand dunes and other similar geographic features in desert regions affect the horizontal sand flux and thus their presence should be accounted in dust parameterizations. Kunin et al. demonstrated how continuous data assimilation of meteorological variables for the first 18 h eliminates the spin-up issues and helps in improving the forecasting skills of WRF-Chem. Chen et al. highlighted the reduction in pollutant concentrations due to the COVID-19 lockdown in Eastern China. Finally, Yang et al. showed that about 22% of the global PM2.5-attributable deaths are caused by desert dust and the newly proposed PM2.5 guideline by the World Health Organization from 10 to 5 μg/m^3 would potentially save one million lives.

We elaborate this Research Topic further to provide extended insights into the broader aspects of dust-climate interactions.

Author contributions

SP prepared the first draft of the manuscript. QJ and DF further expanded and edited the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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