Atmospheric Research 138 (2014) 152–165

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

The global distribution of mineral dust and its impacts on the climate system: A review

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ARTICLE INFO

Article history:
Received 12 July 2013
Received in revised form 5 November 2013
Accepted 6 November 2013

Keywords:
Mineral dust aerosols
Radiative forcing
Semi-directly
Indirect effect
Climate system
Cloud microphysics

ABSTRACT

Mineral dust aerosols, the tiny soil particles suspended in the atmosphere, have a key role in the atmospheric radiation budget and hydrological cycle through their radiative and cloud condensation nucleus effects. Current understanding of spatial and temporal variations of mineral dust, as well as its impacts on the climate system and cloud properties is outlined. Mineral dust aerosols are blown into the atmosphere mainly from arid and semi-arid regions where annual rainfall is extremely low and substantial amounts of alluvial sediment have been accumulated over long periods. They are subject to long-range transport of an intercontinental scale, including North African dust plumes over the Atlantic Ocean, summer dust plumes from the Arabian Peninsula over the Arabian Sea and Indian Ocean and spring dust plumes from East Asia over the Pacific Ocean. Mineral dust aerosols influence the climate system and cloud microphysics in multiple ways. They disturb the climate system directly by scattering and partly absorbing shortwave and longwave radiation, semi-directly by changing the atmospheric cloud cover through evaporation of cloud droplets (i.e. the cloud burning effect), and indirectly by acting as cloud and ice condensation nuclei, which changes the optical properties of clouds (i.e. the first indirect effect), and may decrease or increase precipitation formation (i.e. the second indirect effect). Radiative forcing by mineral dust is associated with changes in atmospheric dynamics that may change the vertical profile of temperature and wind speed, through which a feedback effect on dust emission can be established.

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http://dx.doi.org/10.1016/j.atmosres.2013.11.007

1. Introduction

Among the different components of aerosols in the atmosphere, wind-blown dust is emitted in large quantities over arid and semi-arid regions. Mineral dust, from both natural and anthropogenic sources, is the most abundant atmospheric aerosol component in terms of aerosol dry mass, contributing more than half of the total global aerosol burden (Andreae et al., 1986; Zender et al., 2004; Textor et al., 2006), with an estimated global emission ranging from 1000 to 3000 Mt yr^{-1}, and an average atmospheric dust load ranging from 8 to 35 Mt yr^{-1} (Zender et al., 2004). Therefore, its contribution to the climate system and atmospheric environment is of considerable significance, underlining the essential need for investigation into the origin of dust aerosols, their transport pathways in the atmosphere, and subsequent radiative forcing and impact on the hydrological cycle. Satellite remote sensing analyses show substantial regional variation in terms of mineral dust distribution (Kaufman et al., 2005; Gong et al., 2012). Major sources of dust are located in arid regions, including deserts, semi-arid deserts, dry lake beds and ephemeral channels, where annual rainfall is extremely low (Goudie and Middelton, 2006) and substantial amounts of alluvial sediment have been accumulated (Prospero et al., 2002; Ginoux et al., 2012). In addition to these natural sources, human-induced droughts, disturbance of the land surface and climate variability (i.e. the anthropogenic sources for mineral dust) have also contributed to an increase of mineral dust aerosols within the atmosphere (Prospero et al., 2002; Tegen et al., 2004).

Substantial seasonal variation of atmospheric dust load in response to variation of wind speed and dry conditions (i.e. variation of soil water content and precipitation) has also been observed and simulated (Kaufman et al., 2005; Gong et al., 2012). It is now well known that the maximum dust emission and atmospheric dust load occur in warm seasons. For example, suspended dust from dust sources over the Sahara, the Arabian Peninsula and Southwest Asia is observed most frequently in summer (JJA; Goudie and Middelton, 2006), and maximum dust storm activity over East Asia is observed in spring (MAM; Sun et al., 2001).

Mineral dust aerosols degrade air quality (Prospero, 1999) and adversely affect human health (Pope et al., 2002). They are also a source of iron which can affect marine biogeochemical cycles, thereby contributing to the oceanic uptake of carbon (Jickells et al. 2005). Additionally, mineral dust has a significant influence on the climate system directly by scattering and absorbing solar and infrared radiation (McCormick and Ludwig, 1967; Miller and Tegen, 1998), semi-directly through changes in atmospheric temperature structure and evaporation rate of cloud droplets (i.e. the cloud burning effect; Hansen et al., 1997; Ackerman et al., 2000; Koren et al., 2004), and indirectly in a complex way through impact on optical properties of clouds (i.e. enhancing cloud reflectance by increasing total droplet cross-sectional area; Gunn and Phillips, 1957; Liou and Ou, 1989; Su et al., 2008) and suppression (Ferek et al., 2000; Rosenfeld, 2000) or invigoration (Andreae et al., 2004) of precipitation formation. The aerosol indirect effect is an area of highest uncertainty in the climate system (Ramaswamy et al., 2001; Lohmann and Feichter, 2005), primarily due to high temporal variation and non-uniform distribution of dust aerosol concentration around the globe, and the complex relationship between chemical and physical properties of dust aerosols and cloud microphysics (Chen and Penner, 2005).

Feedbacks are processes in which the output of a system has an impact on its input, with the result that a cyclical chain of actions or reactions is produced. Both negative and positive feedbacks can occur, the former acts to maintain the current status of a system, while the latter tends to produce a run-away change. The relationship between atmospheric processes and dust aerosols is bidirectional, so that while the atmosphere can have a major impact on dust entrainment and its three-dimensional distribution, dust aerosols in turn can have impacts on the atmosphere. Indeed, radiative effects of mineral dust have an impact on atmospheric dynamics. For example, radiative effects of the Saharan dust on the Asian monsoon (Lau and Kim, 2006; Lau et al., 2006) and the West African monsoon (Lau et al., 2009; Sun et al., 2009) have been identified. It has also been noted that direct radiative forcing by mineral dust changes the vertical profile of temperature and atmospheric stability, which in turn influences the wind speed profile within the lower atmosphere (Alizadeh Choobari et al., 2012b). Previous studies indicate that mineral dust aerosols cool the surface and lower atmosphere, and warm the dust layer above during daytime (Alizadeh Choobari et al., 2012b), thereby contributing to establishing a more stable atmosphere (Miller et al., 2004b), and hence decreasing near-surface wind speed (Jacobson, 2002; Perez et al., 2006; Jacobson and Kaufman, 2006; Heinold et al., 2008), but increasing winds in layers above (Alizadeh Choobari et al., 2012b). Such disturbance in meteorological fields may change the emission and transport of dust particles (Yue et al., 2010).

This article is an effort to summarize current understanding of mineral dust distribution in the atmosphere, its radiative forcing and impact on cloud microphysics, as well as its feedback effects on atmospheric characteristics. The paper is organized as follows. Section 2 presents an overview of dust emission, its transport within the atmosphere and deposition processes. The impact of mineral dust on the