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Invited review article

Bioaerosols in the Earth system: Climate, health, and ecosystem interactions

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A B S T R A C T

Aerosols of biological origin play a vital role in the Earth system, particularly in the interactions between atmosphere, biosphere, climate, and public health. Airborne bacteria, fungal spores, pollen, and other bioparticles are essential for the reproduction and spread of organisms across various ecosystems, and they can cause or enhance human, animal, and plant diseases. Moreover, they can serve as nuclei for cloud droplets, ice crystals, and precipitation, thus influencing the hydrological cycle and climate. The sources, abundance, composition, and effects of biological aerosols and the atmospheric microbiome are, however, not yet well characterized and constitute a large gap in the scientific understanding of the interaction and co-evolution of life and climate in the Earth system. This review presents an overview of the state of bioaerosol research, highlights recent advances, and outlines future perspectives in terms of bioaerosol identification, characterization, transport, and transformation processes, as well as their interactions with climate, health, and ecosystems, focusing on the role bioaerosols play in the Earth system.

Contents

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1. Introduction

Primary biological aerosols (PBA), in short bioaerosols, are a subset of atmospheric particles, which are directly released from the biosphere into the atmosphere. They comprise living and dead organisms (e.g., algae, archaea, bacteria), dispersal units (e.g., fungal spores and plant pollen), and various fragments or excretions (e.g., plant debris and brochosomes; Ariya and Amyot, 2004; Brown et al., 1964; Castillo et al., 2012; Cox and Wathes, 1995; Després et al., 2012; Graham, 2003; Madelin, 1994; Matthias-Maser et al., 1995; Rogerson and Detwiler, 1999; Tesson et al., 2016; Womack et al., 2010). As illustrated in Fig. 1, PBA particle diameters range from nanometers up to about a tenth of a millimeter. The upper limit of the aerosol particle size range is determined by rapid sedimentation, i.e., larger particles are too heavy to remain airborne for extended periods of time (Hinds, 1999; Pöschl, 2005).

Historically, the first investigations of the occurrence and dispersion of microorganisms and spores in the air can be traced back to the early 19th century (Ehrenberg, 1830; Pasteur, 1860a, 1860b). Since then, the study of bioaerosol has come a long way, and air samples collected with aircraft, balloons, and rockets have shown that PBA released from land and ocean surfaces can be transported over long distances and up to very high altitudes, i.e., between continents and beyond the troposphere (Brown and Hovmøller, 2002; DeLeon-Rodriguez et al., 2013; Elbert et al., 2007; Gregory, 1945; Griffin et al., 2001; Griffin, 2004; Hallar et al., 2011; Hirst et al., 1967; Imshenetsky et al., 1978; Maki et al., 2013; McCarthy, 2001; Pady et al., 1950; Polymenakou et al., 2007; Pósfai et al., 2003; Proctor, 1934; Prospero et al., 2005; Scheppegrell, 1924; Shivaji et al., 2006; Smith et al., 2013; Wainwright et al., 2003).

Bioaerosols play a key role in the dispersal of reproductive units from plants and microbes (pollen, spores, etc.), for which the atmosphere enables transport over geographic barriers and long distances (e.g., Brown and Hovmøller, 2002; Burrows et al., 2009a, 2009b; Després et al., 2012; Womack et al., 2010). Bioaerosols are thus highly relevant for the spread of organisms, allowing genetic exchange between habitats and geographic shifts of biomes. They are central elements in the development, evolution, and dynamics of ecosystems.

The dispersal of plant, animal, and human pathogens and allergens has major implications for agriculture and public health (e.g., Adhikari et al., 2006; Brodie et al., 2007; Brown and Hovmøller, 2002; Després et al., 2012; Douwes, 2003; Fisher et al., 2012; Fröhlich-Nowoisky et al., 2009; Gorny et al., 2002; Kellogg and Griffin, 2006), and the potential impacts of airborne transmission of genetically modified organisms are under discussion (e.g., Angevin et al., 2008; Folloni et al., 2012; Kawashima and Hama, 2011). Moreover, bioaerosols can serve as nuclei for cloud droplets, ice crystals, and precipitation, thus influencing the hydrological cycle and climate. Especially in pristine air over vegetated regions, bioaerosols are likely to be an essential regulating factor in the formation of precipitation and vice versa (e.g., DeLeon-Rodriguez et al., 2013; Huffman et al., 2013; Möhler et al., 2007; Morris et al., 2014a; Pöschl et al., 2010; Prenni et al., 2013; Sands et al., 1982; Schnell and Vali, 1972; Sesartic et al., 2013; Tobo et al., 2013; Vali et al., 1976). Also in marine environments, particulate matter of biological origin may contribute substantially to the abundance of ice nuclei (Alpert et al., 2011a; Burrows et al., 2013a; Knopf et al., 2010; Lee et al., 2015; Parker et al., 1985; Schnell and Vali, 1976; Schnell and Vali, 1975; Schnell, 1975; Wilson et al., 2015).

An overview of bioaerosol cycling and effects in the Earth system is given in Fig. 2. Some organisms actively emit PBA particles, such as wet-discharged fungal spores, which are emitted with the help of osmotic pressure or surface tension effects, while the passive emission of other PBA particles, like thallus fragments and dry-discharged fungal spores, is mostly wind-driven (Elbert et al., 2007). In the atmosphere, PBA undergo internal and external mixing with other aerosols, including biogenic secondary organic aerosol (SOA) formed upon oxidation and gas-to-particle conversion of biogenic volatile organic compounds, which can influence bioaerosol properties through SOA coatings on PBA particles (Hallquist et al., 2009; Huffman et al., 2012; Pöhlker et al., 2012b; Pöschl et al., 2010).

In the course of atmospheric transport, bioaerosols undergo further chemical and physical transformation, stress, and biological aging upon interaction with UV radiation, photo-oxidants, and various air pollutants like acids, nitrogen oxides, aromatic compounds, and soot (Estillore et al., 2016; Franze et al., 2005; Santarpia et al., 2012; Shiraiwa et al., 2012b). Particle transformation and aging also occur

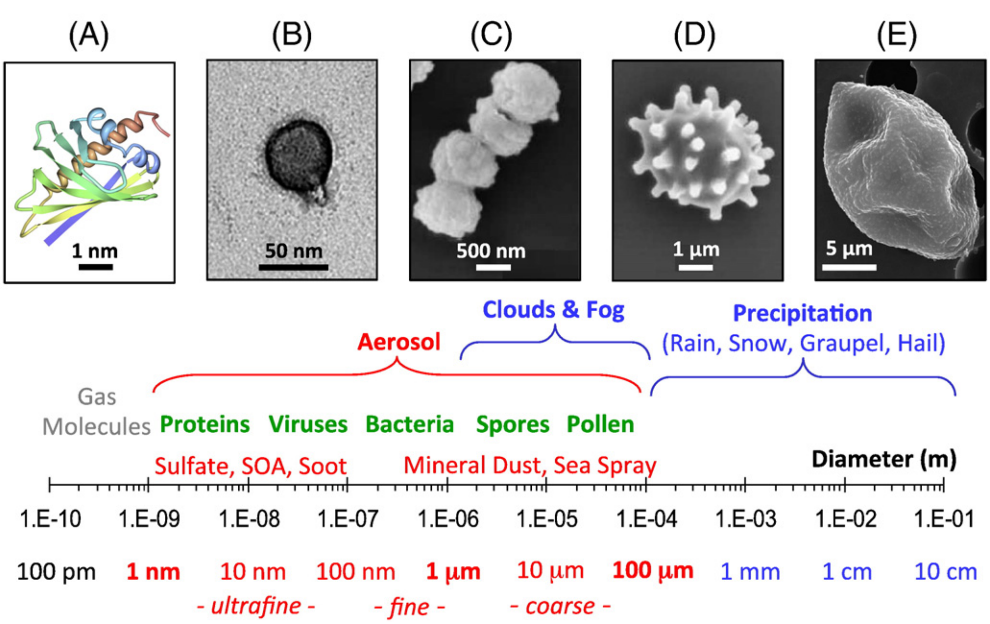

Fig. 1. Characteristic size ranges of atmospheric particles and bioaerosols with exemplary illustrations: (A) protein, (B) virus, (C) bacteria, (D) fungal spore, and (E) pollen grain (adapted from Pöschl and Shiraiwa, 2015). Image A is a model simulation of BetV1 (Kofler et al., 2012; Xu and Zhang, 2009) created with PDB protein workshop 3.9 (Moreland et al., 2005). Images (B–E) are scanning electron micrographs of representative particles from each of the bioaerosol categories listed. Image B reprinted from Whon et al. (2012), copyright 2012, with permission from American Society for Microbiology. Images C and D reprinted from Wittmaack et al. (2005), copyright 2005, with permission from Elsevier. Image E reprinted from Valsan et al. (2015), copyright 2015, with permission from Elsevier.