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Angular scattering of the Gobi Desert aerosol and its influence on radiative forcing

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Abstract

The volume scattering function and the scattering coefficient of the aerosol originating from the Gobi Desert and the Chinese Loess Plateau have been measured in Kyoto using a polar nephelometer and a three wavelength integrating nephelometer. An unambiguous identification of the desert aerosol was possible both by back trajectories and by its specific optical properties.

Despite the larger size of the desert aerosol particles a considerable light scattering occurs at angles between 40° and 140°. This is caused by the irregular shape of the particles. Using the measured scattering phase function, the effect of the desert aerosol particles on the radiative forcing was estimated. Even for an optically thin layer the negative forcing is comparable to the positive forcing by the green house gases. When assuming the particles to be spherical the forcing is by far less, since the resonance effects occurring with the spherical particles cause less side scattering (up to a factor of 3). Therefore, it is essential to use the appropriate scattering phase function.

Keywords: Atmospheric aerosol; Optical properties; Scattering; Phase function; Desert aerosol; Radiative forcing

1. Introduction

Deserts are a large source of airborne particles. On a global scale the desert aerosol contributes 60–1800 Tg/y of the total yearly production of 2900–4000 Tg (Jaenicke, 1988). In South Asia, the Taklamakan Desert, the Gobi Desert and the Chinese Loess Plateau are the major sources. Wind blown dust is the major contributor to atmospheric particles in South Asia. Huebert et al. (2003) estimate a yearly production of wind-blown dust in South Asia between 240 and 650 Tg/y, whereas all other sources (producing sulfates, nitrates, NMVOCs, ammonia, black carbon, organic carbon) amount to 14 Tg/y. Xuan, Liu, and Du (2000) estimate the dust emissions of the Northern China deserts (the main dust source) as 25 Tg/y, an estimate by Zhang (referenced in Xin et al., 2005) is 800 Tg/y of which 50% are deposited back to the source or adjacent areas. The desert aerosol (also known as Kosa or yellow sand in Japan) frequently observed in South East Asia has its origin in the Chinese deserts. The dust is usually mobilized by the Mongolia cyclone, transported

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to altitudes of up to 9 km and from there the transport is anticyclonic and to the Northeast. The dust is transported distances of several thousands of kilometers from the source region to the receptor region and desert dust is found at many locations in SE-Asia. After dust storm events in China, particles having the same chemical signatures were observed in Alaska and at Crater Lake, Oregon, USA (Cahill, 2003). Dust clouds of strong Asian dust storms can even be traced to the Atlantic Ocean (Liu et al., 2003). Of the suspended dust particles 75% are redeposited in the Asian deserts, but 20% of the desert dust particles are deposited on land outside of the Asian desert region (Liu et al., 2003). For spring 2001, the dry and wet deposition outside the source region was modelled: the deposit is estimated as at least 0.5–1 $\mathrm{t\,km^{-2}}$ in whole SE Asia, and obviously by far higher near the source (500 $\mathrm{t\,km^{-2}}$) (Zhao, Gong, Zhang, & McKendry, 2003). In the North Pacific Ocean the deposit for the months April–May 2001 was 0.17 $\mathrm{t\,km^{-2}}$. The main season for wind blown dust is spring and summer. Using a deposition flux density of 1 $\mathrm{t\,km^{-2}\,y^{-1}}$, and a geologically short time interval of 10 000 years, the deposit would have a thickness of 1 cm. Thus, wind-blown dust is also important in soil formation. The lush vegetation in Hawaii is only made possible by a continuous import of long distance transported high nutrient desert dust (Chadwick, Derry, Vitousek, Huebert, & Hedin, 1999; Shaw, 1980). The same applies to the Sahara desert delivering dust to the Amazonas or the Congo basin (Okin, Mahowald, Chadwick, & Artaxo, 2004).

The desert dust particles are generated by mechanical processes and thus are not spherical, many electron micrographs have shown this (see e.g. Falkovich, Gomez, Lewin, Formenti, & Rudich, 2001; Iwasaka et al., 2003). The lidar scattering signal of irregular particles shows less depolarization and at elevations of up to 6 km irregular particles could be identified during dust storm events (Iwasaka et al., 2003). The mechanical production of particles results in particle sizes usually larger than 1 μm. Kontratyev, Ivlev, Krapivin, and Varostos (2006) list a peak in the mass size distribution of 4.5 μm. The number size distributions reported by Alfaro et al. (2003) give a slightly larger size upon conversion to mass size distribution, Cheng, Lu, Chen, and Xu (2005) have measured size distributions with a forward scattering probes during dust storms in northern China and found a peak of the mass size distribution between 3 and 9 μm depending on the dust load. Using the same method Xin et al. (2005) have found a peak of the number distribution at 1.1 μm for dusty days in the Tengger desert. Using the usual assumption of a lognormal size distribution and a geometric standard deviation of 1.8 this gives a peak in the mass size distribution at 3.7 μm. Modeling the production of particles by saltation of sand grains yielded a number size distribution with a main maximum of 0.5 μm and a secondary maximum of 10 μm. This would give maxima in the mass size distribution at 2.7 and 54 μm (Alfaro & Gomez, 2001). Electron microscopic analysis of individual particles of the Sahara aerosol gave a maximum in the mass size distribution of 5 μm (Falkovich et al., 2001).

During long-range transport the majority of the particles settle to the ground. A documentation of the March 21–24, 2001, dust event gives a mass concentration of 6700 $\mathrm{\mu g\,m^{-3}}$ at the source region in the Chinese interior, 4500 $\mathrm{\mu g\,m^{-3}}$ at a distance of 500 km (Chinese Loess Plateau), 1500 $\mathrm{\mu g\,m^{-3}}$ at a distance of 1000 km (Beijing) and 230 $\mathrm{\mu g\,m^{-3}}$ at a distance of 2100 km at a remote island in Japan (Mori, Nishikawa, Tanimura, & Quan, 2003). The life time of the particles in the atmosphere is limited to 1–10 days (Jaenicke, 1988). For example, a 0.3 μm particle has a residence time of 8 days, a 10 μm particle resides 1 day, for 1 and 5 μm the residence times are 5 and 2 days. Since larger particles stay shorter in the atmosphere, the particles settle to the ground more rapidly which changes the size distribution of the aeolian dust: whereas the mass size distribution near the source has a peak at a diameter of 5.5 μm or larger, the peak in Japan occurs at a size of 3.5 μm (Mori et al., 2003). Satellite retrievals yielded a volume size distribution of the particles at Gosan (between Korea and Japan) with a peak at 2 μm (Wang et al., 2003).

Desertification has increased erodible land around deserts in China and Mongolia and dust storms have become more frequent (Wang, Dong, & Chen, 2000). Thus, Gobi Desert events will become more frequent and consequently the mass of suspended particles is expected to increase as well as its effects on the environment in South East Asia. Since desert dust particles can be found half way around the globe, their impact on the environment is gigantic, with much of it still unknown. Desert storm particles have several effects in the environment: fertilization for vegetation, damage to farm products, prevention of acid rain, respiratory diseases, reduced visibility, umbrella to global warming, etc.

Desert aerosol episodes are frequent in Japan (although at a distance of >2000 km from the source), therefore data on size and on chemical composition exist (see e.g. Tohno et al., 2002). The mass size distribution of the desert dust particles has a large peak at a diameter of 2.5 μm containing mainly silicate dust (76%), organic material (12%) and small amounts of SO_4^{2-} (1%), NO_3^- (5%) and Cl, Na and elemental carbon ($<2\%$). The same composition is for particle sizes down to 0.6 μm; the usually dominant particles with a size of 0.5 μm amounts to only 23% of the 2.5 μm peak containing approximately equal amounts of silicate, organics and sulfate. The particles observed during