Major Factors Influencing Local Dust Radiative Forcing

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1 Introduction

Airborne desert dust comprises a major component of natural atmospheric aerosol particles. The dust particles modify atmospheric radiation both in the solar (0.3–5 μm wavelength) and thermal–infrared (5–50 μm wavelength) spectral ranges by scattering, absorption, and emission processes. In this way airborne desert dust particles alter the major radiative energy fluxes within the atmosphere and thus ultimately influence local weather and global climate.

In order to quantify the radiative effects of airborne desert dust particles the concept of radiative forcing is commonly used. A dust–laden (index "dusty") and a particle–free (index "clean") atmosphere are considered. The radiative forcing due to the dust particles contained in the atmosphere is then obtained by:

$$\Delta F = (F_{\downarrow} - F_{\uparrow})_{\text{dusty}} - (F_{\downarrow} - F_{\uparrow})_{\text{clean}} \,. \tag{1}$$

In Equation 1 F represents the radiative flux density (also called irradiance) in units of $\mathrm{W\,m^{-2}}$; the arrows indicate the direction of the flux ($\downarrow$ means downward; $\uparrow$ stands for upward). The irradiances are meant here as spectrally integrated quantities (solar or thermal–infrared).

Usually ΔF is obtained separately for the solar and the thermal–infrared wavelength ranges. Then the sum of the two radiative forcing components is called the net forcing. If the net radiative forcing is positive then there is a win of radiative energy which causes a warming; in the other case a cooling results.

The radiative forcing is a function of altitude. At the top of atmosphere (TOA) Equation 1 reduces to:

$$\Delta F = (F_{\uparrow})_{\text{clean}} - (F_{\uparrow})_{\text{dusty}} \,. \tag{2}$$

This paper summarizes selected aspects of the current knowledge on the radiative effects of airborne desert dust particles. Recent progress is discussed and emerging challenges in this important field of atmospheric research are outlined.

2 Current Knowledge

Presently, the quantification of the local and global radiative effects of airborne desert dust particles is still uncertain. A broad range of values for ΔF is reported in literature, see for example the compilation by Bierwirth et al. (2009). This wide variety of values is not surprising because the radiative effects of desert dust depend on several, widely varying properties of the dust and external parameters. The major dust properties which influence their radiative forcing are optical (dust aerosol optical depth [AOD], single–scattering albedo [ω_0], and asymmetry parameter [g]) or, alternatively, microphysical (effective radius, shape, refractive indices of the dust particles) parameters. Important external parameters are the surface albedo, the vertical dust distribution (mainly influencing the thermal–infrared forcing), and the solar zenith angle (just impacting the solar portion of the dust radiative forcing).

It is well known, that over oceans (small albedo) the solar radiative forcing (both at TOA and the surface) becomes smaller (more negative, stronger cooling) for increasing dust aerosol optical depth AOD. For the TOA this is quite obvious because the upwelling irradiance at TOA increases with AOD (see Equation 2). For a brighter surface (higher surface albedo), however, there occurs increased absorption of solar radiation due to the dust particles but also by the surface (because of multiple reflections). Thus the solar cooling is less in this case compared to the ocean surfaces and may even turn into a warming. In general the solar cooling is stronger at the surface compared to the TOA.

For an increasing asymmetry parameter g the effect on solar radiative forcing is opposite; the solar cooling is reduced in this case. An increased g increases the forward scattering (and therefore also multiple reflections) and reduces the upwelling portion of irradiance; thus the solar radiative forcing at both the TOA and the surface are increasing with increasing g. Over a higher surface albedo the upwelling irradiances at TOA increase as well, thus causing a reduced solar cooling over brighter surfaces.

The radiative effects of an increasing single–scattering albedo ω_0 of the dust particles are more complicated. At TOA the solar warming decreases if ω_0 increases due to lower absorption. However, at the surface the solar radiative forcing increases for increasing ω_0. At TOA the upwelling irradiance is reduced by increased absorption, at the surface the downwelling irradiance is increasingly reduced by more absorbing dust particles. Thus the relative cause of the solar radiative forcing at TOA and the surface is opposite (increasing/decreasing).

3 Recent Advances and Issues

Whereas the radiative effects of desert dust particles described in Section 2 are well established there exist significant gaps of knowledge in several areas, e.g., surface albedo effects, the role of the coarse particle size mode, the impact of the particle shape and of the single–scattering albedo of desert dust particles.

The significant impact of surface albedo in particular on upwelling irradiances is well known, although not adequately considered until recently. Therefore, Bierwirth et al. (2009) performed extensive mapping of this parameter over Morocco. On the basis of these measurements the authors simulated the solar, thermal–infrared, and net radiative forcing of the airborne dust particles and quantified the importance of spectral surface albedo. Their major outcome is depicted in Figure 1. It shows the net radiative forcing of airborne dust particles (Equation 1) as a function of the surface albedo (spectrally averaged). For this plot concurrent measurements of dust particle microphysical properties and surface albedo are used. Figure 1 clearly shows the warming effect of the atmosphere–surface system (TOA data, open triangles) and the cooling at the surface (open squares). A wide range of the spectrally averaged surface albedo over the probed region was observed (0.12–0.33). This variability of surface albedo leads to considerable changes in the net radiative forcing of the dust particles. The sensitivity of the TOA solar and net radiative forcing of the dust with regard to surface albedo is $12\,\mathrm{W\,m^{-2}}$ per 0.1 surface albedo change at TOA, and $9\,\mathrm{W\,m^{-2}}$ per 0.1 surface albedo change at the surface. This highlights the need to consider realistic surface albedo data in dust radiative forcing estimates in models and satellite retrievals.

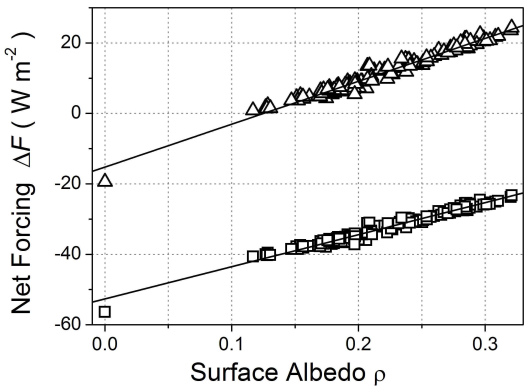

Fig. 1. Net radiative forcing at TOA (open triangles) and the surface (open squares). Adopted from Bierwirth et al. (2009).

With regard to the role of coarse dust particles new findings were published by, e.g., Otto et al. (2007). These recent results showed that particles larger than 3 μm contribute about 50 % to the extinction (in other words AOD). For ω_0 it was shown that neglecting dust particles larger than 1 μm may lead to a significant overestimate of the solar values of ω_0.

Kandler et al. (2009) and Otto et al. (2009) showed that there is a significant fraction of particles in desert dust populations which is of non–spherical shape. Most occurring shapes could be parameterized by spheroidal shapes with aspect ratios between 1:1.3 (small particles) and 1:1.6 (large dust particles). Otto et al. (2009) showed that concurrent lidar measurements could only be reproduced by simulations if the spheroidal shape of the particles is considered. Otherwise (i.e. if spherical particle shapes were assumed) no match between measurements and calculations could be achieved. The non–sphericity had an almost negligible impact on the downwelling irradiance (less than 2 %), but up to 10 % (largest for low Sun) influence on the upwelling solar radiation. In any case, considering non–sphericity acted such that the cooling effect was increased. This is caused by the fact that non–spherical particles exhibit a higher sideward scattering compared to respective spheres. Thus the upwelling solar irradiance is enhanced assuming non–spherical dust particles, and consequently the solar cooling effect is increased.

There is still no consensus about a typical value of ω_0 for desert dust particles in literature. A large variety of data is published; some of them are listed in Table 1. However, this disagreement is no surprise. First, there are inlet problems in airborne in–situ measurements of ω_0. Large particles are not adequately collected which causes systematic over–predictions in airborne measurements of ω_0 (Haywood et al., 2003; Osborne et al., 2008; McConnell et al., 2008). Also, there exists nothing such like a single value of ω_0 of desert dust particles in nature. The particle composition of desert dust is highly variable, therefore no typical value can be given. With different measurement methods (mostly indirect) applied on different scales and in different regions we obtain different results for the single–scattering albedo and thus also for the dust radiative forcing. Besides, as already pointed out 25 years ago by Bohren and Huffman (1983), the refractive index is a property of a material. As soon as mixtures of different materials are involved (which is very common in airborne desert dust particles) usual mixing rules do not always apply and all we get is kind of an effective value for ω_0, which might be useless in specific applications because it represents specific conditions and is valid only if the assumptions made in the retrieval are fulfilled.

4 Emerging Challenges and Conclusions

New issues and demand for further research result from effects due to spatially inhomogeneous dust distributions and surface albedo conditions. It is expected that these three–dimensional inhomogeneities exert significant effects on the derivation of dust radiative effects derived from both, simulations and satellite retrievals. Another upcoming challenge is the appropriate consideration of combined interactions of clouds and airborne desert dust particles.

In conclusion, it is shown in this paper that surface albedo variations over desert regions can have a significant influence on the solar and net radiative forcing of desert dust. It is furthermore concluded that desert dust has mostly a cooling effect over oceans, and a warming effect over highly reflecting desert regions. The widespread

Value of ω_0	Reference
0.78–0.87	Otto et al. (2009)
0.85	Sokolik and Toon (1996)
0.87	Haywood et al. (2001), Lyamani et al. (2006)
0.75–0.96	Otto et al. (2007)
0.86–0.96	Haywood et al. (2003)
0.88–0.89; 0.96-0.97	Meloni et al. (2004)
0.88–0.92	Wang et al. (2006)
0.97	Kaufman et al. (2002), Clarke et al. (2001), Balkanski et al. (2007)
0.98–0.99	McConnell et al. (2008)
0.99	Osborne et al. (2008)

Table 1
Selection of values of single–scattering albedo ω_0 for desert dust from different sources (not complete).

non–sphericity of the dust particles causes a challenge; it yields an additional contribution to the cooling effect.

It is also concluded here that it might be more appropriate not to start with microphysical properties in order to quantify the dust particle radiative effects. Direct measurements of the optical dust particle properties are preferable, otherwise too much uncertainties are coming into play (shape, composition, size). Using the microphysical properties is more suited if the sensitivity of the radiative forcing is investigated.

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