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Does variation in mineral composition alter the short-wave light scattering properties of desert dust aerosol?

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ABSTRACT

Mineral dust aerosol is a major component of natural airborne particulates. Using satellite measurements from the visible and near-infrared, there is insufficient information to retrieve a full microphysical and chemical description of an aerosol distribution. As such, refractive index is one of many parameters that must be implicitly assumed in order to obtain an optical depth retrieval. This is essentially a proxy for the dust mineralogy.

Using a global soil map, it is shown that as long as a reasonable refractive index for dust is assumed, global dust variability is unlikely to cause significant variation in the optical properties of a dust aerosol distribution in the short-wave, and so should not greatly affect retrievals of mineral dust aerosol from space by visible and near-infrared radiometers. Errors in aerosol optical depth due to this variation are expected to be $\lesssim 1\%$. The work is framed around the ORAC AATSR aerosol retrieval, but is equally applicable to similar satellite retrievals. In this case, variations in the top-of-atmosphere reflectance caused by mineral variation are within the noise limits of the instrument.

1. Introduction

1.1. Mineral dust

While not as prevalent in the global atmosphere as maritime aerosol, local dust events dominate total aerosol optical depth in deserts and the surrounding regions during periods of high wind. Long range transport of desert dust (particularly the smaller particles) means that the dust can be seen all over the world, with deposition over the Atlantic and in the Amazon basin being well known occurrences [1]. Saharan mineral dust is thought to play a vital role in the support of vegetation in the Amazon basin and provides nutrient iron to the biogeochemical cycle of the ocean systems [2]. Saudi Arabian dust outbreaks have been linked to weakening of the monsoon trough over India [3].

Mineral dust aerosol is naturally occurring, although desertification caused by changes to climate and to land use (e.g. [4,5]) may be responsible for changes in emission patterns and quantities. Dust is injected into the atmosphere by saltation: a jumping motion whereby already detached, larger particles collide with obstructions on the surface bed, projecting smaller particles into the air [6] (wind alone does not have sufficient energy to remove particles from the surface bed). Since fine mineral dust (light enough to be lofted) is quickly removed from the surface, most of a desert region is not a significant dust source. This means that in the majority of desert regions, surface mineral dust is very coarse. Specific areas such as the Bodélé Depression in Chad, the world's largest dust source [7], have favourable conditions that include strong surface winds, optimum topography, and annual deposition of mineral dust.

Sand composition determines the refractive index (RI), with increasing hematite content leading to increased short-wave absorption (and sand with a more reddish hue) [8]. As such, one would suspect that across the world

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(and indeed within particular regions), variation in the mineralogy of mineral dust and, by extension, in the mineralogy of dust aerosol, would be significant. It would then be expected that the RI of the mineral dust aerosol would vary. Whether or not this causes unacceptable errors in calculations of optical properties is the next question.

Fig. 1 shows how several datasets of mineral dust RI compare in the short-wave. Models have real parts of RI in the visible that range from $n = 1.48 \rightarrow 1.56$ with a median value of $n = 1.53$. Absorption values can vary by almost an order of magnitude. It is likely that the dust sources used to estimate these values are different.

1.2. Satellite aerosol retrievals in the short-wave

Satellite instruments such as (A)ATSR [14], AVHRR [15], MISR [16], MODIS [17], and SEVIRI [18] are radiometers, using specifically chosen wavelengths with relatively narrow spectral bandwidths. For aerosol detection, the channels generally used are around 550 nm, 860 nm, and 1.6 μm since here the size of the aerosols is similar to the wavelength of the measured light, and we are within atmospheric window regions where there is minimal interference from molecular scattering and absorption (a list of available wavelengths is given in Table 1). However, the measurements are inherently under-constrained, no matter how much of the shortwave spectrum is sampled, and as such retrieval methods must make assumptions about the type of aerosol being observed, the mixing between different types, the sizes of these types, and their composition.

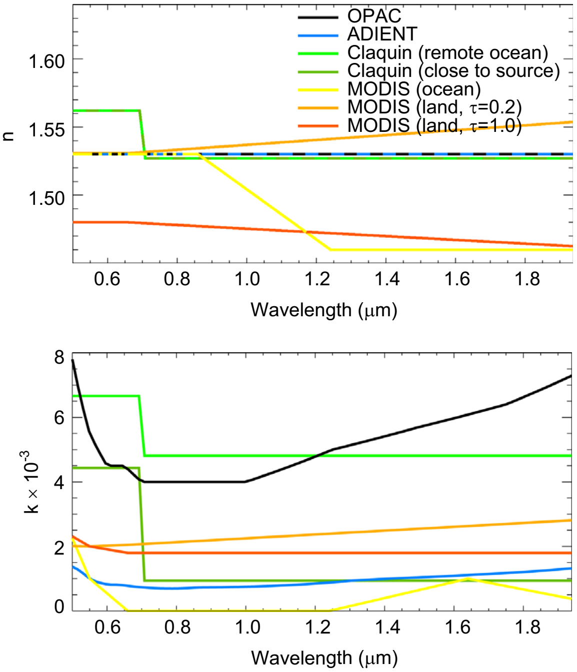

Fig. 1. The real (n) and imaginary (k) parts of desert dust refractive indices as used, or recommended by various science teams. Datasets are: The Optical Properties of Aerosols and Clouds (OPAC) dataset [9]; a literature review of reported aerosol RI to the ADIENT consortium [10]; Claquin et al. [11]; and those used by the MODIS team over ocean [12] and over land (where RI is dependent on the optical depth, τ) [13].

Table 1
Various channels used by broadband radiometers which measure aerosol properties in the visible and NIR. The centres of each channel are given, so (particularly in the case of MODIS) channels can overlap.

Satellite	Channels (μm)
(A)ATSR	0.55, 0.66, 0.87, 1.6, 3.7, 10.8, 12.0
AVHRR	0.63, 0.86, 1.6, 3.7, 10.8, 12.0
MISR	0.45, 0.58, 0.67, 0.87
MODIS	0.41, 0.44, 0.47, 0.48, 0.53, 0.55, 0.56, 0.64, 0.66, 0.67, 0.74, 0.86, 0.87, 0.90, 0.93, 0.94, 1.2, 1.4, 1.6, 2.1, 3.7, 3.9, 4.0, 4.4, 4.5, 6.7, 7.3, 8.6, 9.7, 11.0, 12.0, 13.3, 13.6, 13.9, 14.2
SEVIRI	0.6, 0.8, 1.6, 3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0, 13.4

2. Method

In order to investigate whether variation in desert dust composition is an important factor in determining dust light scattering properties, a picture of global mineral dust RI and its likelihood of atmospheric injection was built up. This could then be used to create a weighted distribution of RI values which are used with a sensible dust size distribution to obtain dust extinction, optical depth, and phase function.

The Earth was divided into gridboxes. Obtaining the mean RI for each selected gridbox is a three step process. First, an approximate soil composition is obtained on a regular grid over the whole Earth, built of common minerals. Next, the RI values of the individual minerals are combined for each soil type, giving a picture of how RI varies geographically. Finally, the world-wide spread is reduced to a histogram of RI values. These are weighted using a simple emissions model so that only areas where dust is likely to be lofted into the atmosphere contribute to the average.

2.1. FAO/UNESCO Digital Soil Map of the World

The FAO/UNESCO Digital Soil Map of the World [19] is a regularly gridded $5' \times 5'$ resolution global map, with each cell containing a mix of soil types. This is equivalent to a resolution of ~9 km × 9 km at the equator, and ~8 km × 9 km at the Bodélé depression, Sahara's largest source of lofted dust [20], with an approximate area of 150 km × 150 km [21]. Using a similar method to Nickovic et al. [22], a list of FAO soil types found in arid areas [23, Table 2] was used. This contains the normalised composition by weight of important dust minerals: in this case illite, kaolinite, smectite, calcite, quartz, felspath (or felspar), gypsum and hematite. The minerals are divided into those found in clay fraction (< 2 μm) and the larger silt fraction ($2 \rightarrow 50$ μm). There is an even larger, sand fraction ($50 \rightarrow 200$ μm), but these particles are too large to be lofted for extended periods so were not included in calculations. The FAO soil 'textures' (coarse, medium or fine) were converted to soil sizes using conversions to dry sieving sizes from Laurent et al. [24, Table 4]. For each $5' \times 5'$ area of land, the FAO map gives up to 8 soil types which make a proportion