Remote Sensing of Environment 156 (2015) 294–309

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Information content of space-borne hyperspectral infrared observations with respect to mineral dust properties

L. Klüser [a],*, J.R. Banks [b], D. Martynenko [a], C. Bergemann [a], H.E. Brindley [b], T. Holzer-Popp [a]

[a] German Aerospace Center (DLR), German Remote Sensing Datacenter (DFD), Wessling, Germany
[b] Imperial College, Space and Atmospheric Physics Group, London, UK

ARTICLE INFO

Article history:
Received 29 January 2014
Received in revised form 19 September 2014
Accepted 29 September 2014
Available online 22 October 2014

Keywords:
Mineral dust
Infrared remote sensing
IASI
Fennec
Information content

ABSTRACT

In principle, observations from hyperspectral infrared (IR) sounders such as IASI (infrared atmospheric sounding interferometer) can be used to simultaneously retrieve dust aerosol optical depth (AOD) and properties such as dust particle size, composition, emission temperature and height. Starting from a compilation of "typical" mineral dust particle size distributions and mineralogical compositions, the information content of dust spectra from Mie simulations and from FTIR (Fourier-transform-infrared spectrometer) measurements (provided by the University of Iowa) is analysed. While the Mie spectra provide a higher number of degrees of freedom for signal (up to 6.7) than the FTIR spectra (up to 5.7), the Shannon information content is slightly lower (3.4) from Mie than from FTIR (3.5). The analysis shows that the spectra provide information on particle size and composition, but information about both cannot be extracted independently owing to the correlations between the different spectra. A dust retrieval approach for IASI probing the spectral shape of extinction has been updated using the Mie and FTIR spectra. Dust properties provided by the retrieval algorithm are: AOD (at 0.55 μm and 10 μm), effective radius, mass-weighted mean diameter, weight-fractions of mineralogical components, IR single scattering albedo and dust layer effective emission temperature. The retrieval uncertainty in each of these parameters is calculated for each IASI pixel. From the retrieved dust layer temperature the dust layer altitude is also inferred using temperature profiles from the WRF numerical weather prediction model.

To evaluate the impact of using the Mie and FTIR spectra within the algorithm, AODs determined using each are compared to AERONET and SEVIRI dust observations. This evaluation suggests that the overall performance of the retrieval in terms of AOD is better for the FTIR version. Evaluation (of the FTIR version) with AERONET coarse mode AOD shows a correlation of 0.73 with RMSD of 0.18 and bias of −0.07. 85% of IASI AOD retrievals are found to be within ±0.2 of AERONET coarse AOD. Evaluating the quality of the other retrieved parameters is more difficult, but we find that the values obtained do show a strong dependence on whether the Mie or FTIR spectra are used. For example, using FTIR spectra results in higher spatial variability in the clay fraction of the retrieved dust compared to Mie. Similar sensitivity is seen in the retrieved particle sizes and single scattering albedo. Indeed, assumptions made concerning the absorption properties of the Mie spectra result in the retrieval of unrealistically low dust layer altitudes, while reasonable values are obtained when using FTIR spectra. Thus it is important to acknowledge that good AOD agreement with independent validation sources does not automatically imply a similar level of quality in the remaining variables.

1. Introduction

Mineral dust in the atmosphere has gained increased interest in the scientific community during recent years owing to its important role in the climate system and its impacts on air quality. Airborne dust interacts directly with solar and terrestrial radiation (e.g. Slingo et al., 2006; Sokolik & Toon, 1999); dust particles can also act as ice cloud nuclei, altering cirrus microphysical properties (e.g. DeMott et al., 2003). Both direct and indirect effects alter the radiation balance, and thus atmospheric and surface heating. They depend on the microphysical, optical and chemical properties of the dust (e.g. Balkanski, Schulz, Claquin, & Guibert, 2007; Johnson & Osborne, 2011; McConnell et al., 2008). Dust induced perturbations to atmospheric stability can alter atmospheric dynamics, further influencing cloud formation and precipitation (e.g. Zhao et al., 2011).

Dust from the Sahara, the largest dust source in the world (e.g. Washington, Todd, Middleton, & Goudie, 2003), acts as an important source of iron for maritime biogeochemistry (e.g. Mahowald et al., 2005) and fertilisation in South America (e.g. Koren et al., 2006). Moreover, desert dust affects regional air quality, also far away from sources, in terms of particulate matter, visibility and even transport of bacteria

---

* Corresponding author.
E-mail address: lars.klueser@dlr.de (L. Klüser).

http://dx.doi.org/10.1016/j.rse.2014.09.036
0034-4257/

(e.g. Prospero, 1999). Planning and forecasting of solar energy resources, especially in subtropical and arid regions, require good knowledge about aerosol due to the low cloudiness of the respective regions. In deserts or semi-deserts, dust is the major contributor to the atmospheric aerosol load. Knowledge about the atmospheric dust load and its microphysical properties from remote sensing is thus of very high importance for the solar energy sector (Schroedter-Homscheidt, Oumbe, Benedetti, & Morcrette, 2013). Consequently there is a strong need for satellite observations of the spatio-temporal distribution of mineral dust in the atmosphere.

Owing to Si–O resonance peaks of silicate minerals in the terrestrial infrared (TIR) (e.g. Kleinman & Spitzer, 1962), narrow-band satellite observations in this spectral region can be used for dust remote sensing (e.g. Ackerman, 1997; Legrand, Plana-Fattori, & N'doume, 2001; Shenk & Curran, 1974). More recently, algorithms seeking to exploit the higher spectral resolution available from TIR sounders for inferring additional information about dust properties or height have also been developed (e.g. Clarisse et al., 2013; DeSouza-Machado et al., 2010; Klüser, Martynenko, & Holzer-Popp, 2011; Pierangelo, Chédin, Heiliette, Jacquinet-Husson, & Armante, 2004).

Most methods for hyperspectral TIR remote sensing of mineral dust rely on imperfect knowledge about surface emissivity. Consequently, up to now, most of these algorithms are only applied over ocean (e.g. DeSouza-Machado et al., 2010; Pierangelo et al., 2004). In Klüser et al. (2011) a method for dust retrieval from IASI (infrared atmospheric sounding interferometer) observations was described which decomposes the IASI spectrum into singular vectors in order to minimise the impact of surface emissivity and atmospheric state. After initially using dust optical properties from the *Optical Properties of Aerosols and Clouds* (OPAC) package (Hess, Koepke, & Schult, 1998), the approach was updated to use laboratory-measured extinction spectra of dust by FTIR (Fourier-transform-infrared spectrometer) (Klüser, Kleiber, Holzer-Popp, & Grassian, 2012). An evaluation with observations from the Fennec campaign in Northern Africa (Washington et al., 2012) showed a generally good performance, but also some limitations of the method, especially with respect to surface emissivity and dust characterisation (Banks et al., 2013). As a result a detailed examination of the information about dust properties contained in IASI signals and the retrieval approach has been performed and is presented here. The new insights are used to further improve the retrieval method. In particular, Mie and FTIR spectra are used as input to the retrieval algorithm in order to evaluate which is better for characterising airborne Aeolian dust.

In section two the current knowledge about the mineralogical, microphysical and optical properties of airborne dust is reviewed, as this information will be of high importance throughout the remainder of the analysis. In section three an analysis of the information content of dust extinction spectra with respect to dust properties is performed. Section four reviews the fundamentals of the retrieval method and describes its updates and new approaches. In section five retrieval results are presented and evaluated using different metrics and methods, with a focus on evaluating differences obtained when using the Mie or FTIR spectra. The discussion in Section 6 is followed by concluding remarks in section seven.

2. Microphysical, mineralogical and optical properties of desert dust

Aeolian dust is characterised by a very high variability in particle sizes (e.g. Haywood et al., 2011; Johnson & Osborne, 2011; Ryder et al., 2013), particle shape (Alexander et al., 2013; Dubovik et al., 2006; Kandler et al., 2007), mineralogical composition (e.g. Engelbrecht et al., 2009; Glaccum & Prospero, 1980; Jeong, 2008; Kandler et al., 2007) and consequently optical properties (e.g. Alexander et al., 2013; Haywood et al., 2011; Sokolik & Toon, 1999). While the assumption of spherical dust particles has been suggested to be a suitable approximation for thermal infrared dust retrievals (Yang et al., 2007), there are other studies (including the work of Hudson, Young, Kleiber, & Grassian, 2008; Hudson, Gibson, Young, Kleiber, & Grassian, 2008; Mogili, Yang, Young, Kleiber, & Grassian, 2008) which indicate that the Mie theory causes large uncertainties in the characterisation of highly resolved spectral infrared extinction. In this study retrieval results using the spherical assumption will be compared to results when the retrieval is run with a more realistic characterisation of dust extinction. Particle size and dust composition have been reported to be critical parameters for the setup of any retrieval algorithm (e.g. Highwood, Haywood, Silverstone, Newman, & Taylor, 2003; Sokolik & Toon, 1999) and so the effects of these parameters are also carefully considered here.

Recently much effort has been spent on characterising aerosol particle size distributions with specific focus on desert dust. Table 1 lists the key characteristics of eight particle size distributions for mineral dust, including the number of lognormal modes and mass-weighted mean diameter D_w of the size distributions. These range from the traditional size distribution for transported mineral dust (MITR) of the OPAC database (Hess et al., 1998) and the mono-modal size distribution used in the Aerosol_cci project of the European Space Agency's Climate Change Initiative (De Leeuw et al., 2013) to four-modal representations of particle size distributions sampled during aircraft campaigns. The campaign data show a very high variability in particle size. During the Dust Outflow and Deposition to the Ocean (DODO) experiment (McConnell et al., 2008) only accumulation mode particles with a radius smaller than 1.5 μm were collected while Ryder et al. (2013) report the abundance of very large particles in dust samples during the Fennec campaign over North Africa. Another size distribution reported by Osborne et al. (2008) for the Dust And Biomass-burning EXperiment (DABEX) is represented by five lognormal modes. The authors also present a “generic distribution” constructed using two lognormal modes, which is the one referred to here as the DABEX size distribution. The eight size distributions mentioned here are presented in Fig. 1. The DODO distributions are restricted to particles with $R < 1.5$ μm (McConnell et al., 2008) and the maximum radius for the MITR distribution is 5 μm (Hess et al., 1998).

Besides particle size the mineral composition of desert dust is the major source of uncertainty in deriving thermal IR optical properties (Highwood et al., 2003; Sokolik & Toon, 1999). Aeolian dust is mainly composed of quartz, clays (such as illite, kaolinite and montmorillonite), carbonates (mainly calcite and dolomite), feldspars (e.g. bytownite, orthoclase and albite) and salts (such as gypsum or halite). Many other components can occur in traces or can provide major contributions to dust composition on local scales (e.g. Kahlaf, Al-Kadi, & Al-Saleh, 1985; Kandler et al., 2007; Sokolik & Toon, 1999). The relative abundances of the major components vary strongly regionally (e.g. Caquineau, Gaudichet, Gomes, Magonthier, & Chatenet, 1998; Sokolik & Toon, 1999).

Table 3 provides a compilation of dust composition analyses from different parts of the world based on the references listed in Table 2. For the purposes of this study we choose to characterise the composition in terms of the eight major components listed in the table. For the sake of clarity, the percentages in Table 3 have been normalised such

Table 1
Names, references, number of modes and mass-weighted mean diameter for the eight dust size distributions used for Mie simulations.

Campaign/ source	Reference	Lognormal modes	D_w
DODO	McConnell et al. (2008)	4	0.93 μm
Gen. DABEX	Osborne et al. (2008)	2 (generic distribution)	2.18 μm
OPAC MITR	Hess et al. (1998)	1	2.53 μm
GERBILS	Johnson and Osborne (2011)	4	2.78 μm
Aerosol_CCI	De Leeuw et al. (2013)	1	4.69 μm
SAMUM-1	Weinzierl et al. (2009)	4	6.40 μm
SAMUM-2	Kandler et al. (2011)	4	11.05 μm
Fennec	Ryder et al. (2013)	4	12.98 μm