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LETTER

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**Abstract**

In this study, an approach in determining effective mixing weight of soot aggregates from dust–soot aerosols is proposed to improve the accuracy of retrieving properties of polluted dusts by means of satellite remote sensing. Based on a pre-computed database containing several variables (such as wavelength, refractive index, soot mixing weight, surface reflectivity, observation geometries and aerosol optical depth (AOD)), the fan-shaped look-up tables can be drawn out accordingly for determining the mixing weights, AOD and single scattering albedo (SSA) of polluted dusts simultaneously with auxiliary regional dust properties and surface reflectivity. To validate the performance of the approach in this study, 6 cases study of polluted dusts (dust–soot aerosols) in Lower Egypt and Israel were examined with the ground-based measurements through AEROSOL RObotic NETwork (AERONET). The results show that the mean absolute differences could be reduced from 32.95% to 6.56% in AOD and from 2.67% to 0.83% in SSA retrievals for MODIS aerosol products when referenced to AERONET measurements, demonstrating the soundness of the proposed approach under different levels of dust loading, mixing weight and surface reflectivity. Furthermore, the developed algorithm is capable of providing the spatial distribution of the mixing weights and removing the requirement to assume that the dust plume properties are uniform. The case study further shows the spatially variant dust–soot mixing weight would improve the retrieval accuracy in AOD_{mixture} and SSA_{mixture} about 10.0% and 1.4% respectively.

1. Introduction

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) working group I (WGI) has reported that the total anthropogenic radiative forcing (RF) was positive during the Industrial Era (IPCC 2013). Earth's energy budget has been perturbed by the significant anthropogenic release of greenhouse gases (GHG) and aerosols to the atmosphere. Atmospheric aerosols are recognised as having an important role in the assessment of climate change. The report concludes the total aerosol RF is approximately -0.9 (-1.9 to -0.1) $W m^{-2}$, exerting direct effects (scattering and absorbing sunlight) and indirect effects (by serving as cloud condensation

nuclei). Nevertheless, aerosol and aerosol–cloud interactions mask a significant portion of GHG warming (Andreae *et al* 2005). Furthermore, it has also been observed that aerosol RF makes the largest contribution to uncertainty in assessment of anthropogenic RF. The direct and remarkable variation of aerosols may be caused by large spatiotemporal variability, complex components and their mixing effects (Liu and Mishchenko 2007, Hansen *et al* 2011, Lin *et al* 2013). For the indirect effect, the 1st indirect forcing is estimated to be between -0.4 and $-1.8 W m^{-2}$, including anthropogenic and natural emissions. However, globally, the effect of anthropogenic emissions is approaching supersaturation with regard to cloud albedo and indirect forcing (Carslaw

et al 2013). In addition, Carslaw *et al* indicated that the limited knowledge of pristine pre-industrial-like environments is important and leads to uncertainty of forcing estimates. Obviously, more comprehensive measurements are needed for accurately mapping the variations of regional and global aerosol RF in the most recent decades, especially because regional aerosol RF might cause extreme weather. Therefore, to further improve the understanding about the impacts of aerosol on climate, the large-scale and/or long-term measurements of aerosol chemical and physical characteristics are urgently needed.

Currently, *in situ* ground measurements and satellite remote sensing are the two available methods for studying aerosol effects. Although *in situ* measurements can provide accurate measurements with high temporal resolution, their low spatial resolution greatly limits their application for RF assessment. On the other hand, satellite imaging could enable researchers to efficiently observe/monitor the spatial differences of aerosols at a regional or global scale. A great deal of effort has been made to utilise satellite imaging (King *et al* 1992, Ackerman 1997, Kaufman *et al* 1997, 2002, Tanré *et al* 1997, Liu *et al* 2002, Levy *et al* 2003, 2007, 2013, Hsu *et al* 2004, 2006, Diner *et al* 2005, Remer *et al* 2005). However, satellite retrievals of aerosol properties have been found to deviate from ground-measurements in some cases (Holben *et al* 1998). For example, the comparison between multi-angle imaging spectroradiometer (MISR) and AEROSOL ROBOTIC NETWORK (AERONET) aerosol optical depth (AOD) data from 2002 to 2004 in Beijing (complex air pollution mixtures usually associate with dust storm events and anthropogenic particulate matter) has shown that the MISR AOD data were substantially lower, especially for heavy aerosol loading cases (Jiang *et al* 2007). In addition, another comparison study also demonstrated that the MODIS monthly mean AOD was underestimated, particularly during the Asian dust storm events in early spring and late winter (Li *et al* 2009). This deviation could be attributed to the mixing of mineral dust and black carbon (BC, the main component of soot aggregates). Most dust particles are observed in a coarse size range with strong light scattering, while soot is in fine size range with strong absorption. The optical properties of dust particles are dramatically altered by mixing with soot aggregates (i.e., polluted dust) (Andreae 1991, van der Werf *et al* 2003, Zhang *et al* 2003, Badarinath *et al* 2004, Radzi bin Abas *et al* 2004, Laskin *et al* 2005, Derimian *et al* 2006, van der Werf *et al* 2006, El-Askary and Kafatos *et al* 2008, Iwasaka *et al* 2009). Previous studies have also reported that the mean differences can be as much as -11.9% for AOD and $+4.1\%$ for single scattering albedo (SSA) between the various considerations of the mixing effect of BC on the optical properties of polluted dusts (Lin *et al* 2013). Thus the mixing effect of BC is crucial and needs to be carefully corrected for in satellite retrievals of aerosol properties.

Consequently, several aerosol types have been considered in the retrieval process to improve the retrieval accuracy (Kaufman *et al* 1997, Tanré *et al* 1997, Diner *et al* 2005, Remer *et al* 2005, Levy *et al* 2007). The general algorithms are derived from the TOA reflectance of satellite data. For the case of mixed aerosols, the TOA reflectances are usually matched as a linear combination by weighting the individual TOA reflectance from each aerosol mode. As is well known, the mixing impacts of aerosol optical properties on the TOA reflectance are nonlinear, hence leading to potential bias in the general retrieval process. Further, there might be more than one combination available for the matching. In short, the simple linear weighted rule with the TOA reflectance does not seem to be satisfactory for resolving the effect of mixed aerosols (e.g., polluted dusts). Therefore, a novel retrieval algorithm was developed in this study to determine the spatial distribution of mixing weights between dust and soot aerosols. The proposed algorithm was further applied to the cases of dust weather over the areas of Sede Boker in Israel and Cairo city in Egypt, as the dust often blows around the Sahara region mixing with smoke generated from biomass burning events (Kaufman *et al* 2002). The performance was validated by ground-based AERONET observations. The results suggest that the novel algorithm could allow researchers (1) to more accurately retrieve aerosols properties by means of remote sensing for polluted dusts, (2) to expand the level of satellite products by providing the spatial distribution of mixing weight and optical properties of polluted dust, and (3) to map the fluctuation of regional RF from dust weather for the investigation related to climate change.

2. Proposed method

Instead of the previous algorithms (linear matching on the TOA reflectance), a database of forward-derived optical properties of polluted dusts, along with the fractions of soot aggregate based on well-developed models, the triaxial-ellipsoidal dust model and the generalised multi-particle Mie-solution model (Xu and Gustafson 2001, Bi *et al* 2009, Li *et al* 2010, Meng *et al* 2010), was established under an external mixing procedure and used for the effective mixing weight determination of dust–soot aerosols in this study.

2.1. Optical properties of polluted dust

Following the models and empirical values employed by Lin *et al* (2013), the bulk (ensemble-averaged) optical properties of the dust and soot particles can be obtained by weighting the probability distribution functions of dust-like aerosol and the number of monomers per aggregate. Under the external mixing procedure, the optical properties of polluted dust can

be expressed as (Levoni *et al* 1997)

$$\langle k^{\text{ext,sca,abs}} \rangle = \frac{w_d \cdot k_d^{\text{ext,sca,abs}} + w_s \cdot k_s^{\text{ext,sca,abs}}}{w_d + w_s}, \quad (1)$$

where $k_d^{\text{ext,sca,abs}}$ and $k_s^{\text{ext,sca,abs}}$ represent the bulk coefficients of extinction, scattering and absorption of dust particles and soot aggregates respectively; w_d and w_s are the number-density mixing ratio of dust and soot. On the basis of this definition, the SSA of polluted dust, $\text{SSA}_{\text{mixture}}$, can be correspondingly derived for the specific wavelength as below

$$\langle \text{SSA}_{\text{mixture}} \rangle = \frac{(1 - w_s)k_d^{\text{sca}} + w_s k_s^{\text{sca}}}{(1 - w_s)k_d^{\text{ext}} + w_s k_s^{\text{ext}}}. \quad (2)$$

Using the concept of the multi-channel retrieval technique of the Deep Blue algorithm (Hsu *et al* 2004, 2006), the database of look-up tables of TOA reflectance in visible spectral bands (0.412, 0.470, and 0.650 μm) of polluted dust can be constructed as the function of aerosol optical depth and single scattering albedo ($\text{AOD}_{\text{mixture}}$ and $\text{SSA}_{\text{mixture}}$), as well as the mixing weight of dust and soot (w_d and w_s). That is, the optical parameters of polluted dust can be obtained from the constructed database in terms of the multi-spectral TOA reflectance observed by the satellite sensor.

2.2. Mixing weight determination

In the previous study (Lin *et al* 2013), a uniform spatial distribution of soot mixing weight has been obtained by including a point value of SSA/refractive index (REFI) from *in situ* measurement (known as the ‘fixed w_s process’). However, the ‘fixed w_s process’ sometimes results in a large discrete jump of k_d^{sca} and k_d^{ext} of pure dust over the source regions. In addition, the determination of mixing weight is greatly limited by site location. The uniform distribution is also usually unable to describe the dust plumes. It is more sensible that the soot mixing weight could be changed with the number-density mixing ratio of dust particles. In order to overcome the shortage of the fixed w_s process, the values of k_d^{sca} and k_d^{ext} were constrained based on long-term observation of *in situ* measurements, such as the data of AERONET. It is referred to as the ‘fixed k_d process’ thereafter. By extracting the look-up tables from a pre-constructed database of polluted dust corresponding to the observation geometries and the auxiliary data of surface reflectivity, the soot mixing weight (w_s) can be determined in accordance with the MODIS spectral TOA reflectance (as the red cross symbol indicates in the look-up table (see figure 1)). The spatial distribution of the soot mixing weight (w_s) thus can be obtained, as well as the $\text{AOD}_{\text{mixture}}$ and $\text{SSA}_{\text{mixture}}$. The schematic flowchart of the proposed approach in this study is illustrated in figure 2.

3. Data and case study

3.1. MODIS data and surface reflectivity

The MODIS sensor, equipped with 36 bands in the visible and thermal infrared spectrum, is a key instrument onboard the NASA Earth Observing System platform, the Terra and Aqua satellite. The Terra satellite passes from north to south across the equator in the morning, while the Aqua satellite passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS can provide almost daily global coverage for the investigation of the land, ocean, and atmosphere. Aerosol products from Terra MODIS and Aqua MODIS have been broadly applied to atmospheric research and are known as ‘MOD04’ and ‘MYD04’, respectively. The MODIS data and products are utilised for optical property retrievals of polluted dust in this study.

For the remote sensing of aerosol, the cloud screening and surface reflectivity fixing are the two steps before aerosol retrieval is performed. The decision of surface reflectance directly affects the accuracy of aerosol retrievals, hence it is of vital importance. In general, there are two approaches to surface reflectance determination for aerosol products (e.g., MOD04/MYD04): the relationships between spectral surface reflectance and pre-constructing a dataset of global surface reflectance. Because the aerosol effects on the shortwave infrared (SWIR) spectral bands are slight in the TOA surface reflectivity, the surface reflectance of the visible band can be reasonably determined based on the SWIR reflectance (Drury *et al* 2008). This reflectance correlated well with the visible reflectance over dark areas (i.e., the dark target method). However, the obscure correlation over bright surfaces (high surface reflectance) results in the limitation of this approach. To overcome this limitation, a dataset of global surface reflectance has been pre-constructed based on the minimum reflectivity technique (MRT) of the Deep Blue algorithm, particularly applied to the bright surface in arid and desert areas. Because the source areas of mineral dusts usually exhibit a bright surface, the MRT is consequently employed in the present study. MODIS surface-reflectance products (MOD09) are employed under a clear-sky situation. The criterion of having an $\text{AOD}_{0.550\mu\text{m}}$ smaller than 0.1 is selected for determining surface reflectance according to previous studies (Herman and Celarier 1997, Koelemeijer 2003). Moreover, to mitigate bidirectional reflectance distribution function effects, the observation geometries of the reference image for surface reflectance has been judiciously selected to be as consistent as possible for the target image in this study.

3.2. Empirical dust properties

The AERONET joint programme, established by NASA and PHOTONS (PHOtométrie pour le

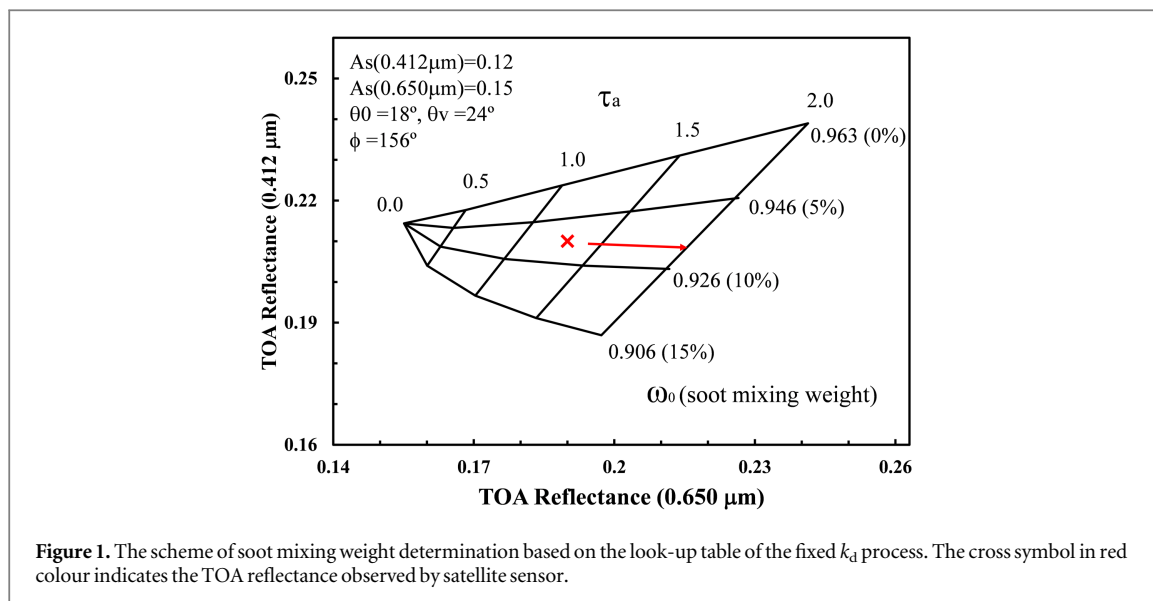


Figure 1. The scheme of soot mixing weight determination based on the look-up table of the fixed k_d process. The cross symbol in red colour indicates the TOA reflectance observed by satellite sensor.

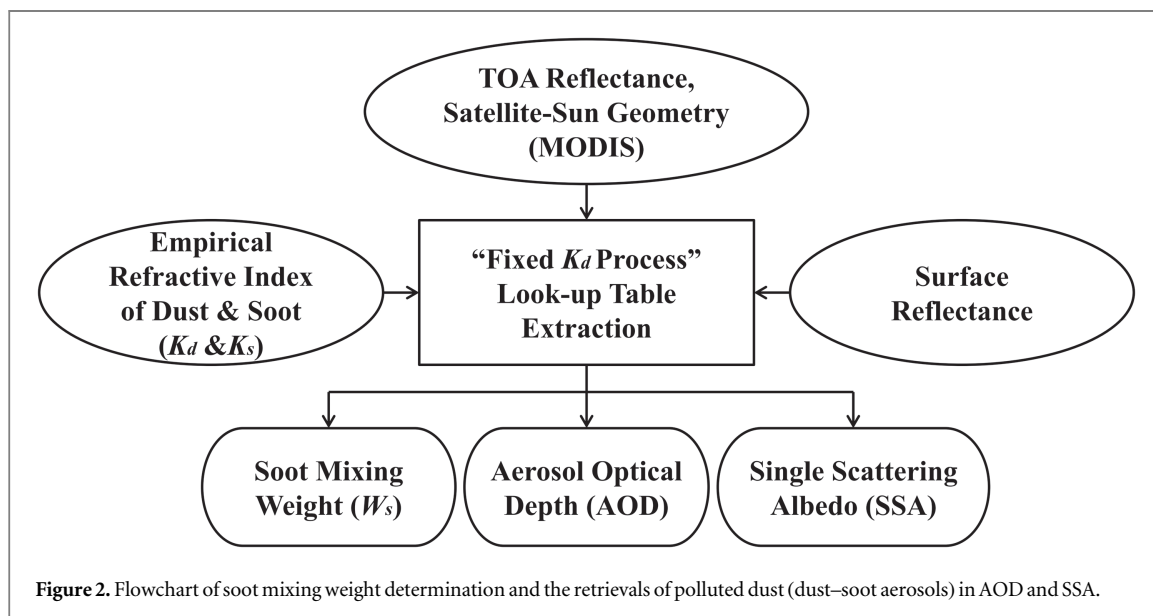


Figure 2. Flowchart of soot mixing weight determination and the retrievals of polluted dust (dust-soot aerosols) in AOD and SSA.

Traitement Opérationnel de Normalisation Satellite; University of Lille 1, CNES, and CNRS-INSU), provides a global, long-term, continuous and readily accessible public domain database of aerosol microphysical and radiative properties by means of ground-based measurements. Therefore, aerosol properties from AERONET are not only the best choice for the empirical property of aerosols but also validation of satellite retrievals. Giles *et al* (2012) have used the long-term AERONET dataset for the optical characteristics of four aerosol categories by grouping up to 19 sites near the source areas of emission, including dust particles, mixed aerosols, urban/industrial pollutants and biomass burning smoke. For the mixed type aerosols, Sede Boker (30.86° N,

34.78° E) and adjacent Cairo (30.08° N, 31.29° E) are the appropriate locations for polluted dust (dust-soot aerosols) observation due to the availability of a complete dataset and because of the dominant aerosol types (Zakey *et al* 2004, El-Metwally *et al* 2008). In this study, the empirical/representative light-absorbing property of regional dust particles can be summarised during the dusty days on the basis of the long-term observations of AERONET sites, both for Sede Boker and Cairo (Prasad and Singh 2007, Wang *et al* 2009). Certainly, Sede Boker is one of the few sites in the world with long-term observations spanning more than 15 years. The long-term measurements have enabled researchers to compile representative statistics in order to evaluate

aerosol absorption properties for the proposed approach in this study. The light-absorbing properties of regional dust particles are principally described by the imaginary part of the REFI. In accordance with historical observations, the empirical value of the REFI of $1.55 + 0.00337i$ and $1.55 + 0.00317i$ at $0.441 \mu\text{m}$ are suggested for the pure dusts at the Sede Boker and Cairo sites, respectively. For the further applicability on a global scale, the empirical value of the REFI is available as well if long term observation can be provided.

3.3. Mixing weight and optical properties

The geographical location of Sede Boker is relatively remote from local pollution sources; however, it lies at the crossroad between downstream dust from the Sahara and the Arabian Peninsula and anthropogenic pollution from Europe and nearby sources (e.g. Cairo city). Similar to the Sede Boker site, the areas around the Cairo site usually receive influence from dust storms that occur from the Sahara Desert. With the local emission of BC from open fires, dust-soot aerosols can be observed often (El-Askary and Kafatos 2008, El-Metwally *et al* 2008). Two dusty cases for each site were selected to validate the performance of the proposed approach in this study, including the different levels of dust particle loading, mixing weight and surface reflectivity, as shown in the true colour images in the left panels of figure 3. The look-up tables corresponded to the geometry and location of each MODIS image extracted from the constructed database of polluted dust for the case studies are displayed in the right hand side panels of figure 3. For the constructed database of polluted dust, the MODIS TOA reflectance is a function of $\text{AOD}_{\text{mixture}}$ and $\text{SSA}_{\text{mixture}}$, as well as the w_s in the look-up table. That is, the properties of polluted dust (AOD, SSA and w_s) can be noted by the location of MODIS TOA reflectance in the τ - and ω - axes of the look-up table, as denoted by the red cross symbols. For the validation of the proposed approach, the values of AOD and SSA from the AERONET dataset and MODIS aerosol products (MOD04/MYD04) are also included in τ - and ω - axes of the look-up tables as the other two symbols demonstrated (black dots and circles).

The first case shown in figure 3(a) is a dust haze mixed with approximately 8.75% weight of soot aggregates, as suggested by satellite observations over the site location of Sede Boker. For the medium level of soot mixing weight, both retrievals of MOD04 and this study are similar to the ground-based measurements. The second case (figure 3(b)) is a dust haze circumstance as well but has a slight loading of dust particles in contrast to first case. These two cases have almost the same magnitude of AOD (approximately 0.7), but the value of SSA obviously decreased (i.e., from 0.915 to 0.899 based on ground

measurements), perhaps due to the mixing effect of soot aggregates. In this case, the result of the mixing weight determination indicated a high-level mixing event (13.75%) with absorbing aerosols (soot-like aerosols) of polluted dust. When compared to the AERONET measurements, the performance of the MODIS aerosol products (MYD04) has an approximately 2.89% overestimation and a 32.96% underestimation in SSA and AOD, respectively, indicating the significance of mixing effects of soot-like aerosols under such circumstances. The similar effect comes up in the third case (c) (see also table 1). It is worth mentioning that the pattern of LUT would vary with a brighter surface (e.g. Sede Boker) under the situations of near nadir observation as figure 3(c) displays.

For the examination of different intensities of dust loading and surface reflectivity in this study, Cairo was selected because the location is frequently on the path of dust storms generated in the Sahara Desert and is often under the influence of heavy anthropogenic pollutants around urban areas. In the third case on 19 February in 2011, dust plumes from the Sahara Desert to the Mediterranean Sea and Nile Delta Region can be clearly observed from the MODIS true colour image shown in figure 3(d). In comparison with MODIS aerosol products, the results of the proposed approach are much improved in the retrievals of AOD and SSA (table 1), indicating the significance of the mixing effect on the retrievals of polluted dust. An obvious dust storm followed the zonal westerlies and passed through the greater Cairo Region; this event is the case study for pure dusts as shown in the image in figure 3(e). The blowing dust plumes might display as 'pure dust' under the circumstances of such a strong storm. According to the multi-spectral MODIS TOA reflectance, the soot mixing weight of dust particles is close to 0.3% at Cairo site, as suggested by the proposed approach, indicating the 'pure dust' status when a satellite passes over. The *in situ* measurement of AERONET also exhibited the same result, supporting the efficient dust model employed in this study.

Meanwhile, MOD04/MYD04 retrievals exhibited the obvious difference from ground measurements in this dust storm event (pure dust case). The noticeable difference may be caused by the properties used in the dust model (REFI and size parameter) and the coarse spatial resolution ($10 \text{ km} \times 10 \text{ km}$) of MOD04/MYD04 products with respect to the point measurement of AERONET. As we know, the dust plumes usually exhibit a discontinuous spatial distribution and then result in a large deviation of TOA reflectance from the MODIS sensor within such a coarse area. Thus the retrievals could be diverse depending on the variance in TOA reflectance. Moreover, surface inhomogeneity with dark areas of the Nile Delta adjacent to the bright surface of Cairo city could be the other factor causing the dissimilarity between MOD04/MYD04 and AERONET

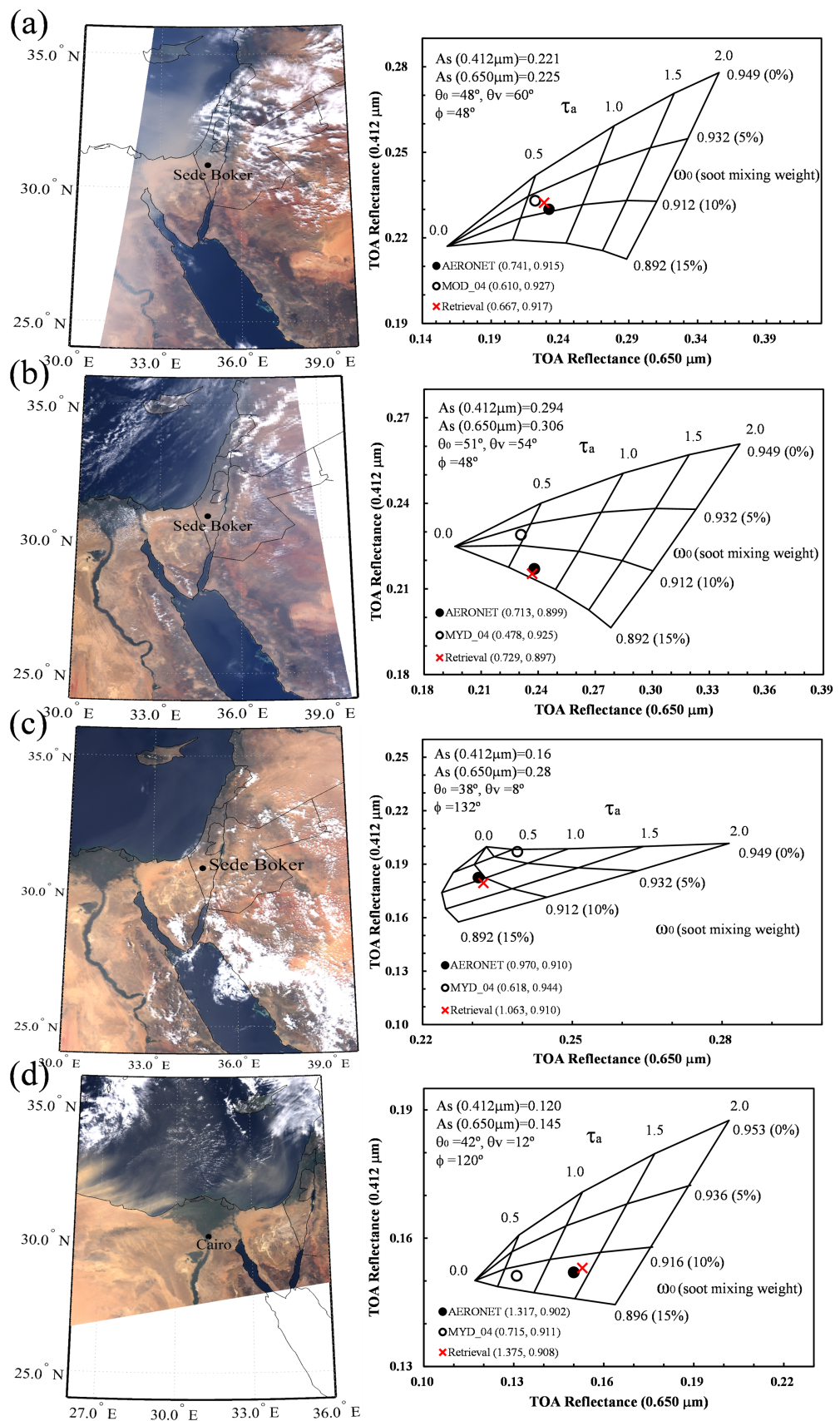


Figure 3. MODIS true colour images over northeast Africa and the Arabian Peninsula at (a) 09:50 a.m. on 24 February 2007, (b) 13:25 p.m. on 20 October 2002, (c) 12:50 p.m. on 12 September 2015 (d) 13:05 p.m. on 19 February 2011, (e) 12:40 p.m. on 27 May 2010 and (f) 13:25 p.m. on 21 March 2012. Black dots superimposed on maps (left panels) indicate the location of AERONET sites. The spectral TOA reflectance observed from MODIS at the location of AERONET sites is denoted by the red crosses on the look-up table (right panels) of the case studies. The corresponding AERONET measurements and MODIS AOD products (MOD04/MYD04) are denoted by solid and hollow black circles on the tables for comparison.

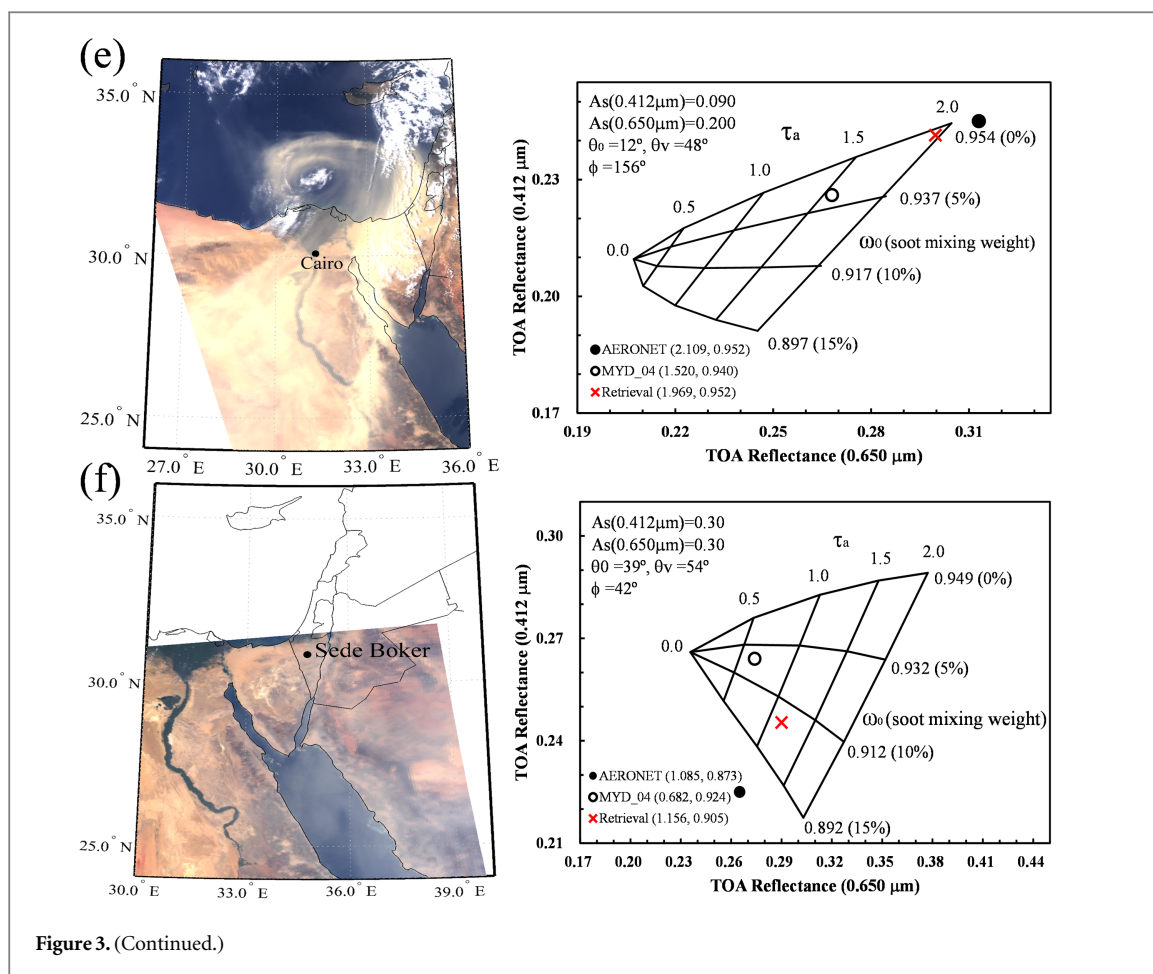


Figure 3. (Continued.)

measurements. Certainly, the Deep Blue algorithm assumes no absorption at 0.670 μm (i.e., $\text{SSA}_{0.670\mu\text{m}} = 1.0$) for pure dusts, and this assumption could be the potential cause of the obvious difference in this case. In fact, the different absorption would cause the variance in SSA of dust particles. For example, 2.6% of the variations in SSA might result in 13.1% variance in the TOA reflectance simulation at 0.650 μm on a bright surface and then further underestimate the MOD04/MYD04 AOD retrievals (Lin *et al* 2013). Therefore, the determination of the empirical absorption (REFI) is significant in retrieving the properties of polluted dusts, as the last case shown at Sede Boker on 21 March 2012 of this study indicates (figure 3(f)). The difference of the SSA retrieval in this study (0.905) from the AERONET measurement (0.873) is evident even as the AOD retrieval is consistent. In review of the MODIS true colour image, the dust plumes were apparently transported from the Arabian Peninsula, potentially exhibiting a different REFI from the counterpart of Sahara dusts used in this case. The result illustrates the essential nature of dust property employed in the mixing weight determination of polluted dusts.

Table 1 displays the summary of the case studies in figure 3. The overall comparison presents the improvement of using the proposed approach in reducing the errors from 32.95% to 6.56% of AOD

and from 2.67% to 0.83% of SSA retrievals on average, and reasonably providing the soot-like mixing weight for the polluted dusts. The comparisons between ground-based measurements (AERONET) and MODIS aerosol products (MOD04/MYD04) can be clearly found from figure 4. On the other hand, the results also suggest that the higher spatial resolution (1 km \times 1 km) could benefit both the accuracy and spatial distribution in the process of retrieving optical properties of polluted dusts.

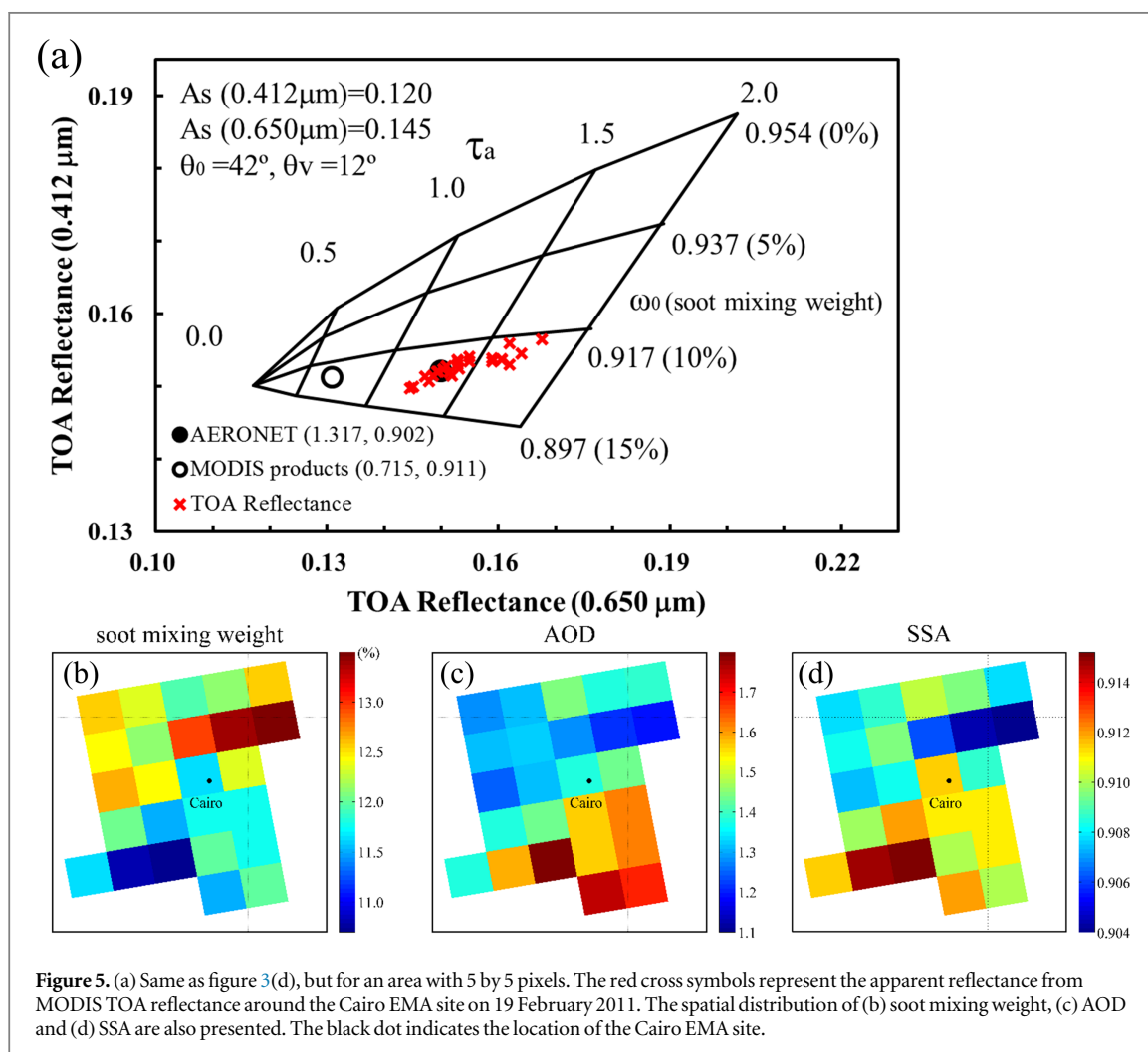
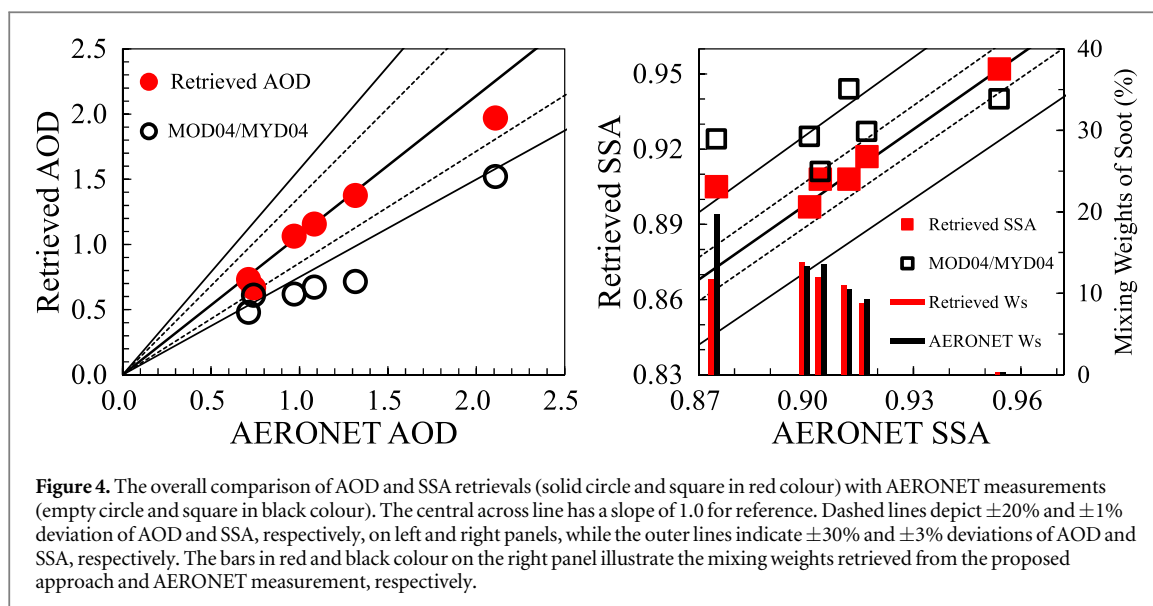
3.4. Spatial distribution of retrievals

Because the case studies show that the soot mixing weight plays the key role in the aerosol retrievals (AOD and SSA), the determination of mixing weight for polluted dust is thus essential, especially over the areas where ground measurement (i.e., AERONET) is absent. Taking the area of the Nile Delta as an example (figure 3(d)), the determination of soot mixing weights and the spatial distribution of polluted dust can be demonstrated in figures 5(a) and (b). The spatial distribution of mixing weight clearly describes the situation of Saharan dusts driven by the westerlies circulation into northwestern Africa, as the MODIS true colour image shown in figure 3(d). Thus, the spatial properties of polluted dust, $\text{AOD}_{\text{mixture}}$ and $\text{SSA}_{\text{mixture}}$ can be accurately retrieved in accordance to the

Table 1. The dust optical properties from (A) *in situ* measurement (AERONET), (B) proposed approach (retrieved) and (C) MODIS aerosol products (MOD04/MYD04) of 6 cases in figure 3.

Case/Site	AERONET (A)			Retrieved (B)			MOD04/ MYD04 (C)		Difference between (A) and (B)			Difference between (A) and (C)	
	AOD	SSA	W_s^a	AOD	SSA	W_s	AOD	SSA	AOD	SSA	W_s	AOD	SSA
(a) Sede Boker (24/02/2007)	0.741	0.915	9.25%	0.667	0.917	8.75%	0.610	0.927	-9.99%	+0.22%	-0.5%	-17.68%	+1.31%
(b) Sede Boker (20/10/2002)	0.713	0.899	13.25%	0.729	0.897	13.75%	0.478	0.925	+2.24%	-0.22%	+0.5%	-32.96%	+2.89%
(c) Sede Boker (12/09/2015)	0.970	0.910	10.50%	1.063	0.908	11.00%	0.618	0.944	+9.59%	-0.22%	+0.5%	-36.29%	+3.74%
(d) Cairo EMA 2 (19/02/2011)	1.317	0.902	13.50%	1.375	0.908	12.00%	0.715	0.911	+4.40%	+0.67%	-1.5%	-45.71%	+1.00%
(e) Cairo EMA 2 (27/05/2010)	2.109	0.952	0.30%	1.969	0.952	0.30%	1.520	0.940	-6.64%	0.00%	0.0%	-27.93%	-1.26%
(f) Sede Boker (21/03/2012)	1.085	0.873	19.75%	1.156	0.905	11.75%	0.682	0.924	+6.54%	+3.67%	-8.0%	-37.14%	+5.84%

^a W_s : mixing weights of soot aggregates.



corresponding weight of mixing soot (see also figures 5(c) and (d)). Figure 5(a) shows, that the soot mixing weight dispensed in the test area ($5 \text{ km} \times 5 \text{ km}$)

displays a noticeable variation, approximately 10.0% to 15.0%, indicating the potential uncertainty of aerosol retrievals could be induced under the assumption of

uniform spatial distribution. In this case, the uncertainty of AOD_{mixture} and SSA_{mixture} retrievals is approximately 10.0% and 1.4%, respectively.

4. Conclusion

We have investigated the impact of the mixing effect of soot aggregates on optical properties of polluted dust (dust–soot aerosols) by means of remote sensing, a novel technique to determine the soot-like mixing weight is proposed in this study by taking advantage of the ‘fixed k_d process’. Using the auxiliary surface reflectivity and regional dust properties, or more specifically, the REFI, the proposed approach can not only provide the spatial distribution of mixing weight, which approaches a more realistic status, but also more accurately retrieves optical properties for polluted dust using satellite data over the desert and arid regions. The results demonstrate the improvement in the MODIS aerosol products (MOD04/MYD04). By considering the mixing weights of dust–soot aerosols for determining the bulk properties in the retrievals, the mean absolute error of the MODIS aerosol products (MOD04/MYD04) can be improved approximately 26.39% in AOD and 1.48% in SSA retrievals, indicating the robust performance of the proposed approach. It is worth noting that the optical property retrievals of polluted dusts from proposed approach are sensitive to REFI of regional dusts (figure 3(f)). The mixing weight, derived using satellite retrievals and radiometric models of dust and soot particles, may contribute to the spatial fluctuation of global aerosols’ radiative forcing in a level of detail that benefits the research of aerosol–cloud interaction and climate change. In addition to the crustal materials targeted in this study (dust–soot aerosols), a number of anthropogenic pollutants from human activities (such as sulphate and nitrate compounds) can still be found around the world. Consequently, assessing the mixing effects of sulphate and nitrate compounds will be a further step in completing the mixing effect of atmospheric aerosols for global monitoring as carried out by the advantage of satellite data.

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