Aerosol Characterization and Direct Radiative Forcing Assessment over the Ocean. Part II: Application to Test Cases and Validation

MARIA JOÃO COSTA
Department of Physics, and Évora Geophysics Centre, University of Évora, Évora, Portugal, and National Research Council, Institute of Atmospheric Sciences and Climate (ISAC-CNR), Bologna, Italy

VINCENZO LEVIZZANI
National Research Council, Institute of Atmospheric Sciences and Climate (ISAC-CNR), Bologna, Italy

ANA MARIA SILVA
Department of Physics, and Évora Geophysics Centre, University of Évora, Évora, Portugal

(Manuscript received 18 July 2003, in final form 19 May 2004)

ABSTRACT

A method based on the synergistic use of low earth orbit and geostationary earth orbit satellite data for aerosol-type characterization and aerosol optical thickness (AOT: \( \tau_a \)) retrieval and monitoring over the ocean is presented in Part I of this paper. The method is now applied to a strong dust outbreak over the Atlantic Ocean in June 1997 and to two other relevant transport events of biomass burning and desert dust aerosol that occurred in 2000 over the Atlantic and Indian Oceans, respectively. The retrievals of the aerosol optical properties are checked against retrievals from sun and sky radiance measurements from the ground-based Aerosol Robotic Network (AERONET). The single-scattering albedo values obtained from AERONET are always within the error bars presented for Global Ozone Monitoring Experiment (GOME) retrievals, resulting in differences lower than 0.041. The retrieved AOT values are compared with the independent space–time-collocated measurements from the AERONET, as well as to the satellite aerosol official products of the Polarization and Directionality of the Earth Reflectances (POLDER) and the Moderate Resolution Imaging Spectroradiometer (MODIS). A first estimate of the AOT accuracy derived from comparisons with AERONET data leads to \( \pm 0.02 \pm 0.22 \tau_a \) when all AOT values are retained or to \( \pm 0.02 \pm 0.16 \tau_a \) for aerosol transport events (AOT > 0.4). The upwelling flux at the top of the atmosphere (TOA) was computed with radiative transfer calculations and used to estimate the TOA direct shortwave aerosol radiative forcing; a comparison with space–time-collocated measurements from the Clouds and the Earth’s Radiant Energy System (CERES) TOA flux product was also done. It was found that more than 90% of the values differ from CERES fluxes by less than \( \pm 15\% \).

1. Introduction

The importance of strong aerosol mobilization and transport episodes is becoming increasingly clear to scientists since these events are usually connected with higher aerosol concentrations in the atmosphere, thus altering the atmospheric composition and affecting delicate mechanisms such as the water cycle (Haywood and Boucher 2000; Ramanathan et al. 2001; Kaufman et al. 2002). This may cause an enhancement/suppression of many related atmospheric processes affecting not only the global, but also the regional and local, climate. It is therefore of extreme importance that such events be accurately detected, characterized, and monitored. The primary natural source of aerosol particles on a global scale is sea salt, followed by soil dust, which is a major contributor especially in subtropical and tropical regions (Houghton et al. 2001). Another substantial natural source of aerosols on a global scale is the biomass burning in Africa, Asia, Siberia, and South America, particularly in the Amazon. For example, smoke from forest fires is a source of strong absorbing aerosols, which reduce the amount of sunlight scattered back to space and lead to absorption of solar radiation within the atmospheric column (Kaufman et al. 2002; Ramanathan et al. 2001).

Satellite-based methods are undoubtedly the only way to proceed for global aerosol studies (King et al. 1999). However, the assessment of the reliability of the retrievals depends on the comparison with independent measurements that allow for the error estimation and eventually the validation of the method.
The low earth orbit–geostationary earth orbit (LEO–GEO) satellite-based method presented in Costa et al. (2004, hereinafter Part I) discussed in detail by Costa (2004) is now applied to three case studies of strong aerosol transport events that occurred over the ocean. The potential of the LEO–GEO synergy had already been discussed by Costa et al. (2002). The aim of the method is to overcome the limitations inherent in LEO and GEO systems by improving the accuracy of the aerosol characterization over that used by methods based exclusively on GEO satellite data and by extending the spatial and temporal coverage of the LEO satellite retrievals to the GEO spatial–temporal scale. This latter point is instrumental for monitoring purposes. The aerosol characterization is derived from the comparison between the Global Ozone Monitoring Experiment (GOME) spectral reflectance measurements and the corresponding simulated spectral reflectances contained in lookup tables (LUTs). LUTs are derived for different aerosol climatological models (Dubovik et al. 2002) and are refined through the variation of some of the size distribution parameters (fine-mode modal radius and fine-mode percentage density of particles), as well as the imaginary part of the refractive index in two spectral regions (0.35–0.50 and 0.70–0.86 μm) and the aerosol optical thickness (AOT). The aerosol characterization that best fits the measurements is considered to be the derived aerosol model. The aerosol optical quantities (single-scattering albedo, phase function, and extinction coefficient) are obtained from Mie calculations considering spherical aerosol shapes. These quantities are used to derive the AOT from GEO satellite measurements, avoiding the use of aerosol models from the literature. The AOT at the GEO spatial–temporal scale together with the aerosol optical quantities characterizing a certain aerosol event are applied to estimate the top-of-atmosphere direct shortwave aerosol radiative forcing (TOA DSWARF).

GEO meteorological satellite sensors normally only host a broadband channel in the visible (VIS) spectral range. However, the method is open to the possible future use of GEO satellite measurements from new-generation sensors such as the Spinning Enhanced Visible and Infrared Imager (SEVIRI) flying on board the Meteosat Second Generation (MSG) (Schmetz et al. 2002). These sensors are expected to bring improvements to the retrievals because they are equipped with narrower VIS spectral bands, and additional spectral information is anticipated from the channels in the near-infrared (NIR) spectral region, which are complementary to those from GOME that is limited to the ultraviolet (UV)–VIS (Burrows et al. 1999).

The spectral aerosol single-scattering albedo and aerosol phase function derived from GOME high spectral resolution measurements are used to characterize the aerosol transport events and to model the atmospheric radiation. They are successively compared with simultaneous and collocated retrievals from the ground-based sun–sky photometer Aerosol Robotic Network (AERONET; Dubovik and King 2000).

The AOT values retrieved at the temporal and spatial scales of the GEO satellite Meteosat are also compared with AERONET measurements and with the official aerosol products from the Polarization and Directionality of the Earth Reflectances (POLDER) instrument (Goloub et al. 1999; Deuzé et al. 2000) on board the Advanced Earth Observing Satellite (ADEOS) and with the Moderate Resolution Imaging Spectroradiometer (MODIS) (Tanré et al. 1997) on board the Terra spacecraft. In addition, the AOT values are checked against results derived from aerosol models available in the literature. This not only validates the results of the new method, but also shows that there is a notable improvement when considering the GOME-derived aerosol quantities instead of relying on a climatologically based characterization.

The TOA shortwave (SW) flux is in turn compared with the TOA flux product (dataset CERES Terra FM1 Edition1 ES8) of the Clouds and the Earth’s Radiant Energy System (CERES; Wielicki et al. 1996), on board Terra, with the purpose of controlling the flux modeling quality and indirectly the estimated TOA DSWARF, as suggested by Christopher and Zhang (2002).

The following section illustrates the selected case studies. Section 3 describes results and their validation, and section 4 summarizes conclusions from the test and validation exercise.

2. Case studies

Three case studies of aerosol transport over the ocean were selected: 1) dust transport over the Atlantic Ocean, 2) dust transport over the Indian Ocean (Arabian Sea), and 3) a smoke transport event over the South Atlantic Ocean. The geographical areas of each of the case studies are illustrated in the maps in Fig. 1. The black squares indicate the locations of the AERONET stations used as ground reference.

The event of the first case study occurred at the beginning of June 1997 over the Atlantic Ocean (Fig. 1a), where massive amounts of dust are frequently blown westward out of the African Sahara Desert, especially during the Northern Hemisphere summer. This is due to the almost complete absence of rainout during this season, which prevents the deposition of dust particles and allows their long-distance transport. The Meteosat-6 full-disk image corresponding to the VIS spectral channel shown in Fig. 2a demonstrates the extent and intensity of the dust event, as evident from the wide brighter region over the North Atlantic Ocean cloud-free region. Figure 2b shows the corresponding AOT map obtained from the present methodology using the GOME-derived aerosol properties. Higher AOT values are distinguished in the region where the dust aerosol plume is located. The dust aerosol absorption map from the Total Ozone Mapping Spectrometer (TOMS) on
Fig. 1. Maps of the geographical areas for each of the selected aerosol case studies: (a) dust transport event over the North Atlantic Ocean, (b) dust transport event over the Arabian Sea, and (c) biomass burning event over the South Atlantic Ocean. The black squares indicate the location of the AERONET stations used for comparison: (a) CV, Cape Verde; DK, Dakar; BZ, Banizoumbou; (b) BA, Bahrain; KA, Kaashidhoo; NZ, Nes Ziona; and (c) AI, Ascension Island; EP, Etosha-Pan; SW, Swakopmund; and ZA, Zambezi.

Fig. 2. (a) Meteosat-6 full-disk VIS imagery from 8 Jun 1997, slot 25 (1200–1230 UTC), when the dust was blowing off the Sahara Desert and crossing the Atlantic Ocean (courtesy of EUMETSAT). (b) The corresponding aerosol optical thickness map derived using the present methodology.

board the Earth Probe (Fig. 3a) allows for the detection of absorbing aerosol particles, such as dust and smoke, based on their absorption properties in the UV spectral region. The grayish spots over the dominating background color delimit the aerosol absorption areas and therefore the presence of absorbing particles. The corresponding selected AERONET stations for the above-mentioned case study are the Cape Verde Islands...
FIG. 3. Absorbing aerosol particles detected by the Earth Probe TOMS on (a) 8 Jun 1997, (b) 14 Jul 2000, and (c) 9 Sep 2000. TOMS data allow for distinguishing between different types of aerosol particles based on their absorbing properties in the UV. The brighter regions over land and darker regions over the ocean represent strong aerosol absorption.

A spatial and temporal analysis of the GOME-derived aerosol optical properties (see Part I for details) results in case-specific average dust/biomass burning aerosol quantities, such as spectral extinction, single-scattering albedo, and phase function, assuming the aerosol plumes maintained their physical characteristics during the duration of each one of the case studies. These results were compared with ground measurements from AERONET’s official inversion product (Dubovik and King 2000). The AERONET algorithm derives the aerosol
size distribution, the complex refractive index, and the single-scattering albedo from spectral sun and sky radiances measured by the network's sun–sky photometers. Level-1.0 data are used in this case since no level-2.0 inversion products were available for the present case studies. The AERONET size distribution and complex refractive index were used as input for Mie calculations in order to obtain the aerosol optical properties, such as the phase function, characteristic of the aerosol event under study according to the recommendations of Dubovik et al. (2000). The Angström exponent is also calculated from the AERONET spectral AOT values and compared with the value obtained from GOME.

Figure 4 shows the values of the single-scattering albedo for the three case studies together with those from aerosol models in the literature. The vertical error bars represent the standard deviation of the GOME-derived single-scattering albedo (around 0.04). AERONET single-scattering albedo values have an accuracy of the order of 0.03 for dust and biomass burning events with AOT at 0.44 μm > 0.5 (Dubovik et al. 2000). These error bars are not reported in the graphs in Fig. 4 for clarity. In Fig. 4a the GOME-derived values for the Sahara dust event are compared with AERONET's values taken in Dakar and Banizoumbou, sites that were overpassed by dust plumes several times during this period; results from the AERONET inversion algorithm were not available from Cape Verde and they are not shown. The single-scattering albedo is in good agreement with the AERONET measurements, especially for the Dakar site in the red spectral region with differences lower than 0.01, whereas there is a slight underestimation in the blue region, reflecting higher aerosol absorption than that reported by the AERONET Dakar measurements (differences of 0.016 at 0.4 μm and of 0.013 at 0.488 μm). The climatological desert dust model derived from the AERONET data at Cape Verde (Dubovik et al. 2002) presents considerably higher spectral single-scattering albedo values outside the error bars associated with GOME-derived results, with differences ranging between 0.05 at 0.4 μm and 0.07 at 0.694 μm.

The fact that the AERONET single-scattering albedo values in Banizoumbou are lower, particularly in the red spectral region (higher aerosol absorption) with differences that reach 0.035 at 0.86 μm, is probably connected with the site location being well inland, where the aerosol load might have been higher and the land surface properties are quite different from those of the ocean surface. The desert plume mixes over the ocean with marine aerosol particles characterized by very low absorption, which is reflected in higher single-scattering albedo results. Nevertheless, the values corresponding to the Banizoumbou AERONET site are still within the GOME-derived error bars.

In the dust transport case illustrated in Fig. 4b, the GOME-derived spectral single-scattering albedo values are in between measurements taken at Bahrain and Kaashidhoo AERONET sites. The Bahrain site registers the lowest single-scattering albedo values in this case, differing from the GOME results of 0.01 in the blue and of 0.02–0.03 in the red. Numbers referring to Kaashidhoo are higher, hinting to a less absorbing aerosol type, with differences from the GOME results being between 0.04 (blue) and 0.02–0.01 (red). A possible explanation of this difference is that the Kaashidhoo site, situated at the extreme southwest part of the area, was less affected by the dust plume than the other site and the single-scattering albedo values in reality characterize a mixture of dust and marine particles. Once again the
the climatological model representative of desert dust over Bahrain (Dubovik et al. 2002) induces higher single-scattering albedo values (less absorbing aerosol), with differences from the GOME-derived values of around 0.08.

A comparison between the single-scattering albedo for the dust aerosol in the two cases indicates that the desert dust from the Middle East absorbs more than that which originated from the Sahara Desert: the difference is 0.03 in the blue and 0.05 in the red.

The results for the biomass burning episode are reported in Fig. 4c. Note that the aerosol properties from the Swakopmund AERONET site do not correspond to the period of study (6–13 September 2000) but to a few days later (15–24 September 2000) because of problems with data availability: the comparison was therefore done assuming the smoke plume maintained its characteristics during the second period, which is not necessarily true. GOME-derived values are in good agreement with AERONET measurements in Ascension Island, differing by 0.005 in the blue and by 0.017–0.01 in the red. Yet, AERONET results for Zambezi and Swakopmund are a little lower, with greater differences for the lower wavelengths (always less than 0.03).

Again, these sites are located inland and closer to the fires, especially Swakopmund. Moreover, the two ground and satellite datasets are close in time but not coincident. The biomass burning case displays an optimal agreement with the AERONET values reported for the African savannah (Dubovik et al. 2002), with differences being lower than 0.004, except at 0.86 μm where a difference of 0.02 is observed. Note that this difference is lower than the accuracy limit of AERONET retrievals and of GOME-derived standard deviations and therefore these results are considered quite good.

The Ångström exponent obtained from AERONET measurements and the GOME-derived values are plotted in Fig. 5. The numbers from the satellite-based algorithm are relative to the mean aerosol properties retrieved over the area; therefore, a constant value was derived for each case. The Ångström exponent values are very low in the first case (Fig. 5a), which is typical of dust aerosol particles presenting a dominant larger particle mode, unlike biomass burning aerosols where the Ångström exponent values are larger. The GOME-derived value was 0.04, which is generally in good agreement with results from Cape Verde, Dakar, and Banizoumbou. Also for the Arabian dust, although the values are higher (0.20), the accordance with the AERONET values taken at Bahrain and Kaashidoo sites is quite acceptable (Fig. 5b). The values of the Ångström exponent from AERONET increase significantly for the biomass burning aerosol type (Fig. 5c) as was expected and again the GOME retrieval matches this increase with a value of 1.55.

Figure 6 presents the graphs of the phase function at 0.4 μm. GOME-based retrievals are reported together with AERONET values and models taken from Dubovik et al. (2002). Figure 6a shows that the phase function obtained from GOME is lower than the AERONET values for scattering angles between 80° and 150°, and the same tendency is found for the Cape Verde literature model. In the Arabian dust case the underestimation of the GOME-derived phase function, as well as of the Bahrain literature phase function values, is still appreciable although less marked. This could be connected with artifacts arising from considering in both aerosol models (ours and Dubovik’s) spherical aerosol shapes for desert dust particles. As pointed out by Dubovik et al. (2002), the nonspherical shape for desert dust particles is responsible for deviations of the phase function at scattering angles ≥90°. On the contrary, the biomass-
b. Aerosol optical thickness retrieved from GEO satellite measurements

1) Sahara dust event

The AOT is derived from Meteosat broadband VIS measurements using both the GOME-derived aerosol properties and the desert dust model described by Dubovik et al. (2002) derived from AERONET measurements in Cape Verde. The results are compared in Fig. 7, where the frequency histogram of the AOT values is shown. The processing of about 5 million Meteosat pixels during the event in the first half of June 1997 over the area shown in Fig. 1a supports the histogram in Fig. 7. Clearly, for both aerosol models a bimodal distribution of the AOT can be distinguished, which corresponds to a background marine situation and to the Saharan dust transport event. While the modalities correspondent to the background marine particles (low AOT values) are very similar, substantial differences can be noted for optical thickness values related to the dust event where larger AOT values are obtained. This shows how significant the impact that the choice of the adequate aerosol properties can be on the AOT in the presence of high aerosol loads in the atmosphere.

The AOT derived from Meteosat data was compared with measurements from the selected AERONET sites. The AERONET AOT values used in the comparisons are level 2.0 (quality assured) and have an accuracy of about 0.02 (Holben et al. 1998). The Meteosat AOT pixels were enclosed in a box of $0.5^\circ \times 0.5^\circ$ centered on the geographical location of the ground-based station, then spatially averaged, and the respective standard deviation computed, discarding all cloud–land-contaminated pixels. AOT values from the AERONET stations were taken for about 1 h before and 1 h after the Meteosat scan time over the area. Values were time averaged and the standard deviation over the 2-h period
computed. The AERONET averaged optical thickness was taken for comparisons if the correspondent standard deviation was $<0.2$. With regard to the spatially averaged AOT derived from Meteosat, values $>1.0$ are retained if the correspondent standard deviation is $<0.5$.

Figure 8 shows the scatterplots of the optical thickness retrieved from Meteosat using GOME-derived aerosol properties (Fig. 8a) and the Cape Verde literature aerosol model (Dubovik et al. 2002; Fig. 8b), versus the AERONET measurements taken in Cape Verde and Dakar, for the first half of June 1997 after the screening of data. The horizontal error bars represent the standard deviation of AERONET measurements over the 2-h period, whereas the vertical error bars represent the spatial variation in the optical thickness over the chosen area. The dotted lines delimit the $\pm15\%$ error, representative of the Meteosat instrumental error (Part I). In general, there is quite good agreement between the AOT values retrieved from Meteosat using GOME-derived aerosol properties and the ones measured by the AERONET sites. Differences are attributed to the scatter of Meteosat-retrieved values within the averaged area. Nevertheless, the accordance is better than in the case of the aerosol models from the literature, which seems to show a tendency to underestimate the AOT values. In fact, 74% of the AOT values retrieved from Meteosat using GOME-derived aerosol properties have an agreement of better than 15% with AERONET AOT measurements, whereas for the AOT values derived using the Cape Verde desert dust model (Dubovik et al. 2002) only 62% of the values fall within this error limit. This fact proves that, although Meteosat has only a broadband channel in the VIS spectral region, its data can be used for aerosol studies when associated with the GOME-derived aerosol properties. The retrieval accuracy improves significantly over that which can be achieved by using literature aerosol models, as is shown by the comparisons with AERONET measurements.

The AOT values retrieved from Meteosat-6 are also compared to the corresponding POLDER product (Goloub et al. 1999). For this purpose, the values of AOT $<2.0$ are averaged over coincident cells of $0.5^\circ \times 0.5^\circ$ and compared within the time coincidence window $<15$ min. The cell is retained for comparison if at least 40% of its pixels fulfill the AOT $<2.0$ condition.

The scatterplots of Meteosat versus POLDER AOT for the aerosol characterization with the GOME-derived aerosol properties are displayed in Fig. 9a for the whole of June 1997. Error limits are $\pm15\%$ (dotted) and $\pm30\%$ (dashed). Data are somehow scattered, and this may be due to differences in the algorithms. If all AOT values are compared, 23% of the values lie within the $\pm15\%$ limit and 44% within $\pm30\%$. If only values of AOT $>0.4$ are considered (aerosol event situation), percentages increase to 36% ($\pm15\%$ error limit) and 70% ($\pm30\%$ error). When the Cape Verde literature dust model is considered, a higher number of cases is obtained within the same limits: 29% and 53% for the $\pm15\%$ and $\pm30\%$ error limits, respectively, when all values are considered; 45% and 80% for the $\pm15\%$ and $\pm30\%$ error limits, respectively, if only AOT $>0.4$ values are retained. Note that the LUTs built for the retrieval of the optical thickness from POLDER have 0.6 as the largest
AOT value (Goloub et al. 1999). This means that higher AOT values are obtained by linear extrapolation, possibly leading to an under- or overestimation of the values. The highest value considered acceptable for the validation and shown in the figure is 2.0, since it may be considered representative of a typical desert aerosol dust load for these events (Tanré et al. 1997). On the other hand, aerosol absorption is taken into account in the present method, but not considered in the POLDER algorithm, and this may be the cause of the systematic differences observed in the plots. In order to compare results on the same ground, that is, the POLDER situation, the values of the present method were reprocessed assuming a pure scattering approximation. In this case, the optical thickness was multiplied by the single-scattering albedo at 0.55 μm. The value obtained from Mie calculations of the single-scattering albedo from the GOME retrieval is 0.88 while that from the literature desert class is 0.96. The new results are now illustrated in the scatterplot of Fig. 9b. After matching the retrieval conditions of the GEO-retrieved AOT values to those of POLDER, the two sets of AOT values come closer to each other when using the GOME-derived aerosol properties (see Fig. 9b). Thirty-four percent of the values in the scatterplot agree within ±15% and when only AOT > 0.4 values are taken, the percentage increases to 55%. As for the ±30% limit (dashed lines in the graphs in Fig. 9), 55% and 86% are obtained, respectively, when all the AOT values are considered and only AOT > 0.4 are taken. When using the desert dust literature model, the agreement between Meteosat and POLDER AOT is worse with an underestimation trend of the optical thickness: 26% and 52% for the ±15% and ±30% error limits, respectively, when all values are considered; 38% and 77% for the ±15% and ±30% error limits, respectively, if only AOT > 0.4 values are considered.

The frequency distributions of the ratio between the AOT obtained from POLDER and that from Meteosat displayed in Fig. 10 summarize the results for June 1997. The left column refers to the optical thickness derived from Meteosat using the GOME aerosol properties plotted (a) considering aerosol absorption and (b) matching its values to the conditions of POLDER, that is, multiplying them by the single-scattering albedo. In case a it seems that there is a systematic overestimation tendency of Meteosat data. This difference is minimized in case b when the results are matched to POLDER conditions, which means considering nonabsorbing aerosols and using GOME-derived properties as illustrated in Fig. 10b.

The graphs in Fig. 11 show the frequency percentage of the ratio between POLDER and Meteosat AOTs during June 1997. Even though the desert dust properties are derived from GOME data gathered in the first half of June, the results refer to the whole month. The aim is to detect significant differences and set a temporal limit on the validity of the aerosol optical properties retrieved from GOME spectral reflectance fitting. The inspection of the graphs, which show once more Meteosat results with and without aerosol absorption (Figs. 11a and 11b, respectively), suggests that the agreement between Meteosat and POLDER retrievals is slightly worse for the last week of June than for the rest of the month. This may be an indication that retrieved aerosol
classes at that time were no longer representative of the aerosol-loaded atmospheric situation and should have been updated.

2) Arabian Dust Event

The AOT retrieved from Meteosat-5 pixel radiances in July 2000 over the area in the Arabian Sea depicted in Fig. 1b are compared with AERONET measurements taken at Bahrain and Nes Ziona. Results are reported in the scatterplot in Fig. 12. The conditions imposed for the comparisons are those applied to the Sahara dust
event. In general, the agreement between ground-based measurements and satellite retrievals using the aerosol properties derived from GOME spectral measurements is good, with 40% of the values within $\pm 15\%$ (dotted lines in Fig. 12) and 54% of the cases within the same limit if only AOT $> 0.4$ values are considered. Furthermore, the agreement is better than that resulting from the application of the literature aerosol model (not shown), which once again discloses a tendency to underestimate the AOT values. In fact only 32% of the AOT values derived using the literature aerosol model are within the agreement limit of $\pm 15\%$, and this total rises up to 45% if only AOT $> 0.4$ are considered.

The retrieved AOT values are also compared with the corresponding values out of the MODIS official aerosol product (version 004). Coincident areas of $0.5^\circ \times 0.5^\circ$ are averaged and compared, keeping the best time coincidence (maximum 15-min difference). Figure 13 shows the scatterplots of Meteosat versus MODIS AOTs for the case of aerosol characterization with GOME-derived aerosol properties. Results refer to the period from 10 to 16 July 2000. There is again better agreement between the results from both algorithms when the aerosol properties obtained from the GOME spectral measurements’ inversion are used in the Meteosat retrievals: 55% of data agree within $\pm 15\%$, whereas the agreement drops down to only 45% when the Bahrain desert dust model is used. If the limit is relaxed to $\pm 30\%$, then the numbers are 75% and 70% for the GOME-derived aerosol properties and the literature model, respectively. Under the same conditions, the Bahrain desert model results in 62% of the cases being within $\pm 15\%$ and 90% of the cases within $\pm 30\%$. Note that the greatest differences stemming from the use of the different aerosol models (GOME derived and literature) are obtained for the lowest error limit ($\pm 15\%$). This indicates that the use of the GOME-derived aerosol properties improves the accuracy of the retrieved AOT values.

3) BIOMASS BURNING EVENT

AERONET measurements from Swakopmund were not available during the period of the event, and Etosha-Pan and Zambezi are located inland. Therefore, there were no coincident Meteosat AOT results since presently the method is limited to retrievals only over the ocean. The only AERONET site used for AOT comparisons is Ascension Island (see Fig. 1c) and results are shown in Fig. 14. Only a limited number of coincident data points are available for AERONET values $< 0.7$. If only AOT $> 0.4$ values are considered, 78% of them are within $\pm 15\%$, against a 54% resulting from the use of the African savannah literature model. If all values are retained, 34% are confined within the $\pm 15\%$ limit for the GOME-derived properties and 27% for the literature aerosol model.

AOT values computed from Meteosat VIS radiances are also compared with the official MODIS AOT product during the period of the event (6–13 September 2000). Once again, coincident areas of $0.5^\circ \times 0.5^\circ$ are
averaged and compared, thus ensuring the best temporal match between MODIS and Meteosat image acquisitions. Figure 15 shows these comparisons for the case of aerosol characterization with GOME-derived properties. When using the GOME-derived properties, 48% and 60% of the cases are within the $\pm 15\%$ and $\pm 30\%$ error limits, respectively, when all values are considered. If only values with AOT $> 0.4$ are considered, 70% and 96% of the cases are within the $\pm 15\%$ and $\pm 30\%$ error limits, respectively. As for the African savannah literature model, 32% (within $\pm 15\%$) and 57% (within $\pm 30\%$) are the figures when all the AOT values are considered, and 40% (within $\pm 15\%$) and 87% (within $\pm 30\%$), if only AOT $> 0.4$ results are taken.

A first estimate of the accuracy of the GOME/Meteosat-derived AOTs at 0.55 $\mu$m inferred from AERONET comparisons is $\pm 0.02 \pm 0.22 \tau_a$ when all AOT values are examined. For aerosol event situations where AOT $> 0.4$, the estimate of the AOT accuracy is $\pm 0.02 \pm 0.16 \tau_a$. The accuracy is not as good as that published for MODIS AOT ($\pm 0.03 \pm 0.05 \tau_a$, dust excluded) by Tanré et al. (1997), and this is probably due to inherent problems in the satellite data used (GOME pixel dimension, Meteosat calibration; see Part I for details). Nevertheless, the proposed methodology is not merely suited for AOT monitoring, but also for deriving the TOA direct SW aerosol radiative forcing at the GEO temporal scale. Other methods based exclusively on LEO satellite data lack this feature that is relevant for climate applications. On the other hand, if the methodology is applied to better calibrated and high space-time resolution MSG SEVIRI data, it is conceivable that the AOT accuracy of the present method will significantly improve.

c. DSWARF assessment from GEO satellite measurements

The TOA SW flux modeled with the Second Simulation of the Satellite Signal in the Solar Spectrum (6S; Vermote et al. 1997) radiative transfer code is compared to the CERES TOA SW flux product as a way of verifying the radiative transfer calculations and checking the validity of the calculated LUTs (see details in Part I). The fluxes are modeled considering a tropical vertical atmospheric profile (McClatchey et al. 1971), a Lambertian ocean surface, and the GOME-derived aerosol properties. The comparison was carried out only for the aerosol events occurred during the year 2000, that is, the dust event over the Arabian Sea and the biomass burning episode since for the 1997 dust event there were no CERES data available. Results are shown in Fig. 16. The data points correspond to averages over 0.25 $\times$ 0.25° wide areas within the study regions (Figs. 1b and 1c) for cloud- and land-free pixels. A slight tendency of the model to underestimate the values with respect to CERES results is observed. Nevertheless, the agreement between the measurements and the correspondent modeled data is in general quite good. In the first case (Arabian dust event), 96% of the modeled values present an agreement with CERES data better than $\pm 15\%$ (dotted lines in the plots), whereas in the second case (biomass-burning episode) 93% of the values are within the same level of agreement.
Fig. 16. Scatterplots of the modeled TOA SW flux vs CERES TOA SW flux for the geographical areas presented in Fig. 1: (a) dust transport event over the Arabian Sea, 10–16 Jul 2000, and (b) biomass-burning event over the South Atlantic Ocean, 6–13 Sep 2000. The dotted lines represent the ±15% error limit.

The TOA DSWARF is then retrieved over the study areas, using the AOT values previously estimated from Meteosat VIS measurements and LUTs calculated using the aerosol properties obtained from GOME (Part I). Figure 17 shows the variation of the TOA DSWARF with the AOT at the reference wavelength of 0.55 μm calculated from Meteosat VIS radiances considering the GOME-derived aerosol properties for each of the three aerosol events considered. The points in the graphs correspond to pixels in the imagery and what varies is time during the event and the geometry of the illumination. Note how the points fall along well-defined curves that correspond basically to different solar zenith angles. The graphs show that the TOA DSWARF per unit AOT is greater for the Saharan dust event than it is in the other cases. This is probably related to the fact that the spectral single-scattering albedo values are higher in this case, thus leading to more radiation reflected at the TOA. For the Arabian dust and biomass-burning cases, the lower single-scatt-
tering albedo values result in higher aerosol absorption, possibly leading to atmospheric heating. In these cases the surface and atmospheric radiative forcings become more relevant for climate studies than does the TOA forcing (Satheesh and Ramanathan 2000).

The instantaneous TOA DSWARF values obtained from Meteosat data were averaged for the 24-h period over the case study regions to obtain the mean daily TOA DSWARF variation during the events shown in Fig. 18 together with the daily mean variation of the AOT values derived from Meteosat pixel radiances considering GOME aerosol optical properties. The variation of the daily mean TOA DSWARF with the daily mean AOT is also shown in the smaller graphs in Fig. 18. Note again that larger negative TOA DSWARF values were derived over the Atlantic Ocean for the Saharan dust, meaning that in this case the earth–atmosphere system “loses” more energy, which results in a cooling of the system. In particular, note that the TOA DSWARF is at a maximum on 7 June 1997 when the AOT value is also the highest (Fig. 18a). For an AOT = 1.0 the computed daily mean TOA DSWARF is −19.0 W m\(^{-2}\), which is quite close to the value of −20.7 W m\(^{-2}\) published by Liu et al. (2003) for Saharan dust aerosols. In the other two events, lower daily mean TOA DSWARF values are observed and therefore the cooling is not so pronounced. The Arabian dust event is associated with a daily mean TOA DSWARF of −15.8 W m\(^{-2}\) for an AOT = 1.0 and the biomass-burning case shows a value of −16.0 W m\(^{-2}\) for the same AOT.

4. Conclusions

Aerosol optical properties were derived from GOME high spectral resolution measurements and used to estimate the AOT and the TOA DSWARF from Meteosat VIS measurements over selected areas and during significant aerosol transport episodes. The proposed method is a valid tool for aerosol characterization and optical thickness monitoring over the ocean, especially for strong aerosol events, provided that a geostationary satellite covers the area of interest. This potential is demonstrated using data from the Meteosat operational service (positioned at 0°, 0°) and from the Indian Ocean Meteosat-5 coverage service (positioned at 0°, 63°E).

Comparisons of model-derived aerosol properties, such as the single-scattering albedo, Angström exponent, and phase function with independent retrievals from several AERONET sites, show that the agreement is generally quite good. The single-scattering albedo values obtained from AERONET are in fact always within the error bars associated with GOME retrievals, resulting in differences being always lower than 0.041. In addition, the spectral behavior of the single-scattering albedo is well reproduced from GOME retrievals for all case studies.

The comparison of the AOT retrieved from Meteosat with independent measurements from AERONET shows a good agreement as well, when GOME-derived aerosol properties representative of the aerosol situation are used. A first estimate of the derived AOT accuracy for all values is ±0.02 ± 0.22τ\(_a\), and ±0.02 ± 0.16τ\(_a\).
for events when AOT > 0.4. Reasonable agreement is also found from comparisons with the AOT products obtained from POLDER and MODIS data. Comparisons with POLDER show that 34% of the AOT values agree with POLDER within a ±15% limit, whereas with MODIS the agreement increases to 55%. When only values of AOT > 0.4 are considered, the agreement is even better, with 55% of the values being within the ±15% limit for POLDER, and 70% of the values within the same limit for MODIS. Results demonstrate that the choice of the aerosol model is crucial for accurate retrievals and consequently the atmospheric characterization should, as much as possible, be representative of the actual situation. This implies that the atmospheric characterization should be regularly updated while conducting studies over long time retrievals. On the other hand, the great potential of the method for the study of strong aerosol transport events is also demonstrated.

The TOA SW fluxes retrieved from Meteosat and those estimated from the CERES product compare well, with more than 90% of the values differing from CERES fluxes for less than ±15%. The DSWARF estimates for the three aerosol events show that the effect at the TOA is higher for the Saharan dust in June 1997. As expected, the stronger absorption of aerosol particles in the Arabian region and over the South Atlantic results in a lower negative TOA DSWARF probably increasing the radiative forcing at the surface. In addition, the daily mean TOA DSWARF per unit optical thickness is estimated to be −19.0 W m⁻² for the Saharan dust event (in agreement with Liu et al. 2003), −15.8 W m⁻² for the Arabian dust event, and −16.0 W m⁻² for the biomass burning episode.

Acknowledgments. Funding was provided by the Portuguese Foundation for Science and Technology under Grant PTDC/CTA/42917/2001. One of the authors (VL) acknowledges support by the Italian Space Agency under the grant Sinergia GERB-SEVIRI nello studio del bilancio radiativo a scala regionale e locale. The senior author was supported by the Subprograma Ciência e Tecnologia do 2º Quadro Comunitário de Apoio. Meteosat imagery was kindly made available by EUMETSAT. AERONET data are available online (http://aeronet.gsfc.nasa.gov/) thanks to NASA, CNES, and CNRS. AERONET investigators and their staff deserve special thanks for establishing and maintaining the sites where the data used in this investigation were obtained. POLDER aerosol parameters are products derived from the data of the CNES POLDER instrument on board NASA’s ADEOS. MODIS data are courtesy of NASA Earth Science Enterprise and the official algorithms were developed by the MODIS Science Teams. They were processed by the MODIS Adaptive Processing System (MODAPS) and Goddard Distributed Active Archive Center (DAAC), the latter being in charge of archiving and distribution. CERES data were provided by the Atmospheric Sciences Data Center at NASA Langley Research Center. Three anonymous reviewers significantly contributed to the improvement of the manuscript and are gratefully recognized.

REFERENCES


Sathish, K. V., and V. Ramanathan, 2000: Large differences in tropo-