Assessing the Errors in Shortwave Radiative Fluxes Inferred from the Geostationary Earth Radiation Budget (GERB) Instrument in the Presence of Dust Aerosol

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(Manuscript received 26 February 2007, in final form 12 October 2007)

ABSTRACT

The Geostationary Earth Radiation Budget (GERB) instruments flying on the Meteosat Second Generation series of satellites provide a unique tool with which to monitor the diurnal evolution of top-of-atmosphere broadband radiation fields. GERB products, which have recently been released to the scientific community, include aerosol information in addition to the observed radiances and inferred fluxes. However, no account of the anisotropic characteristics of aerosol has been incorporated in the radiance-to-flux conversion, which uses angular distribution models developed for clear or cloudy conditions. Here an attempt is made to quantify the impact of this omission in the shortwave (SW), focusing on dust-contaminated scenes. An observationally based representation of dust is used to develop a theoretical angular distribution model, which is tested through comparison with observed GERB radiances. For dusty scenes that have been processed as clear ocean, applying the dust model to convert GERB radiances to fluxes reduces the SW reflected flux by an average of approximately 12 W m$^{-2}$ relative to the original GERB fluxes. This value ranges from $-4$ to $+55$ W m$^{-2}$, depending on observation geometry and dust loading. For dusty scenes that the GERB processing has treated as cloudy, GERB fluxes are generally smaller than values obtained using the dust-specific model. On average, over the time period studied here, the two effects partially cancel, and the overall mean difference is 2.5 W m$^{-2}$. However, it is shown that this cancellation is highly sensitive to the location and time period under consideration.

1. Introduction

The potential for dust aerosol to modify strongly the components of the earth’s radiation balance has been recognized for some time (e.g., Carlson and Benjamin 1980; Fouquart et al. 1987; Ackerman and Chung 1992; Sokolik and Toon 1996; Tegen et al. 1996). Recent aircraft campaigns have indicated that in the presence of heavy Saharan dust loadings the reflected shortwave (SW) flux at the top of the atmosphere (TOA) can be enhanced by over 100 W m$^{-2}$ over dark ocean scenes (Haywood et al. 2003). Longer-term studies of Saharan dust TOA radiative forcing efficiency based on twice-daily observations from the Clouds and the Earth’s Radiant Energy System (CERES; Wielicki et al. 1996) and Moderate-Resolution Imaging Spectroradiometer (MODIS; Salomonson et al. 1989) instruments flying on the polar-orbiting Terra and Aqua satellites suggest a diurnal mean efficiency of approximately 35 W m$^{-2}$ per unit optical depth ($	au$) during the June–August season (Li et al. 2004).

Broadband radiance and flux products from the Geostationary Earth Radiation Budget (GERB) instrument (Harries et al. 2005) flying on the Meteosat-8 were recently released for analysis by the scientific community. Because of the satellite’s geostationary location at 0°, 3.5°W, GERB has an excellent view of the African continent, the Atlantic Ocean, and the Mediterranean Sea, as indicated in Fig. 1. With a spatial resolution of $\sim50$ km (at nadir), and a temporal resolution of $\sim15$ min coupled with narrowband information available from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument (Schmetz et al. 2002) available at the same temporal resolution, GERB has the potential to monitor the radiative effect of Saharan dust storms as they evolve in time throughout the day. Algorithms to detect dust over ocean (Brindley and Russell 2006, hereinafter BR06) and to quantify the amount present (Brindley and Ignatov 2006, hereinafter BI06) using
SEVIRI have been developed and are contained within the GERB products, but the results are not used to inform the radiance to flux conversion. Instead, the SW radiance-to-flux conversion relies on an independent cloud detection and cloud optical depth retrieval algorithm (Ipe et al. 2004). Angular distribution models (ADMs) developed for clear or cloudy conditions derived from observations made by the CERES instrument on board the Tropical Rainfall Measuring Mission (TRMM) satellite (Loeb et al. 2003) are then applied to the GERB radiances according to the viewing and solar geometry and the results of the cloud detection algorithm. Results from the dust detection algorithm show that dust, in particular when present at higher loadings, is sometimes falsely identified as cloud by the cloud detection scheme: in these cases fluxes are determined by application of cloudy ADMs. In other cases, the dust does not affect the cloud detection and so clear-sky ADMs are used to convert the observed radiance to flux. Differences in anisotropy between dust aerosol and the assumed scene type could result in biases in the GERB fluxes; we expect this to be particularly pronounced over ocean when a clear ADM is applied because of the highly anisotropic nature of ocean scenes. In the work described in this paper, we seek to quantify the impact on the GERB SW fluxes of neglecting the effect of dust aerosol anisotropy and to develop a method that could be employed to account for the aerosol effect in the radiance-to-flux conversion. With this aim, in section 2, we introduce the GERB product. We also provide an indication of the quality of the aerosol optical depth retrievals contained within the product over the period under consideration for the aerosol model used in the GERB processing and two further aerosol representations. In section 3, we recap different approaches that could be used to perform a radiance-to-flux conversion in the presence of dust. In section 4, we test the performance of the two aerosol models introduced in section 2 in terms of their ability to match the angular distribution of the observed GERB radiances. We also assess the performance of the different approaches highlighted in section 3 by analyzing the variability of derived flux fields. In section 5, we use the best-performing model and approach identified in section 4 to quantify the likely impact of neglecting the effect of dust aerosol on the GERB SW fluxes and derived dust radiative efficiency. Conclusions to be drawn from this study are then provided in section 6.

2. GERB product information

Full details of the GERB instrument, including a description of the data-processing chain and data archival arrangements are given in Harries et al. (2005). GERB averaged, rectified, and geolocated (ARG) level-2 products were released for use by the scientific community on 11 May 2006 and at the time of writing could be accessed from the GERB Ground Segment Processing System (http://ggsps.rl.ac.uk).

For the work presented in this paper we have used the GERB high-resolution (HR) level-2 shortwave radiances and associated fluxes, contained within the GERB HR level-2 product (hereinafter GHR2) for the period April–June 2006. The GHR2 products utilize the SEVIRI observations to provide information on the scene variability within each GERB footprint and so interpolate the GERB observations of radiance from the GERB native resolution (~50 km × 50 km at nadir) to a 3 × 3 SEVIRI pixel resolution (~10 km × 10 km at nadir; Dewitte et al. 2008). As part of the GERB processing, shortwave fluxes are determined from the radiances by the application of the appropriate CERES TRMM ADMs chosen according to the GERB scene identifier (ID), which consists of a cloud detection algorithm and a fixed land surface map. For consistency with the observational resolution at which these ADMs were built up, this radiance-to-flux conversion is made at the spatial scale of the GHR2 product.

Also contained within the GHR2 product is a dust identification flag based on the approach described in BR06, and three aerosol optical depth (AOD) fields corresponding to the solar reflectance bands on
SEVIRI. Both are provided over ocean only, with the latter fields produced using the algorithm developed initially for the Advanced Very High Resolution Radiometer (AVHRR; Ignatov and Stowe 2002) and subsequently adapted for SEVIRI (BI06).

Details of the performance of the dust flag and AOD retrievals made in dusty conditions are provided for selected case studies in BR06 and BI06. For these cases, retrievals performed using either the Ignatov and Stowe generic aerosol model (used operationally in GERB products) or a dust-specific nonspherical model (Dubovik et al. 2002a,b) showed very good agreement with matched MODIS (Remer et al. 2005) and cloud-screened Aerosol Robotic Network (AERONET; Holben et al. 1998; Smirnov et al. 2000) observations. Nevertheless, to test the quality of the AOD retrievals over a wider range of solar/viewing geometries, comparisons over the period analyzed here are presented. Dust events were selected by eye using the AERONET time series to search each site for consistently elevated AOD levels through a given day (daily mean AOD > 0.5 with more than 10 observations during the day), in conjunction with the requirement that the Ångström exponent be less than 0.3 (implying large aerosol particles). Likely dusty days were then verified using both the dust flag information and a visual inspection of red–green–blue images derived from the shortwave SEVIRI channels. Based on these selection criteria, data from 40 days were retained. Figure 2a shows a scatterplot of AOD at 0.63 μm as obtained from selected AERONET coastal sites against coincident GHR2 (Ignatov and Stowe aerosol model) AOD retrievals. Figures 2b and 2c show the same information but respectively use the Dubovik dust model and an aerosol representation based on the tropical maritime model of Hess et al. (1998), used routinely by the CERES team to derive aerosol contaminated broadband fluxes (see section 3), to obtain the AOD retrievals. In all cases, the retrievals are constrained to be within ±7.5 min and ±0.5° of the AERONET measurements. Two further quality controls are imposed: 1) to avoid the possibility of coastal contamination, only retrievals situated more than one HR pixel away from a land point are retained when forming the spatial averages (this procedure removes ~10% of all retrievals) and 2), to remove cloudy pixels that have been falsely identified as dusty, the standard deviation of the broadband SW radiances of the pixels forming the averages must be less than 10% of the mean values. The threshold on the second filter is somewhat arbitrary but represents the best compromise of achieving the removal of obviously cloudy points while retaining the vast majority of AOD retrievals (~1% of all retrievals are removed). In each plot, the vertical error bars in indicate the 1-standard-deviation (1 σ) spread that is due to the spatial averaging employed. Note also that the AERONET observations compose level-1.5 data and may not have had a final calibration applied, adding a small uncertainty to these AODs.

From Fig. 2, good agreement is seen between the AERONET and GHR2 values, using either the Ignatov and Stowe or the Dubovik dust aerosol model to perform the AOD retrievals. However, there is clearly an increased scatter if the Hess et al. tropical maritime model (Fig. 2c) is employed, suggesting that this model is a less appropriate tool for deriving AOD from narrow-band measurements for the dusty cases identified here. Further analysis of the AOD observations, separated first according to AERONET site (essentially satellite viewing zenith) and then according to solar geometry, revealed no coherent dependence of the level of agreement seen on either parameter. Overall, the results obtained using the Dubovik model (Fig. 2b) show the highest degree of correlation with the AERONET values, but there is no compelling evidence to suggest that this model is performing significantly better than the Ignatov and Stowe representation for these cases. However, in the context of this study, note that the latter representation was derived empirically using a combination of narrowband AVHRR reflectance observations and Mie theory. Because the size distribution associated with the representation is a monomodal lognormal with a mode radius of 0.1 μm, there is no expectation that it can be used to provide reasonable broadband radiances. Therefore, it is not included in the broadband studies in the following sections. This is not the case for either the multimodal Hess model or the observationally based Dubovik aerosol model.

3. Radiance-to-flux conversion method—Available options
In general, the conversion from radiance to flux is achieved using

\[ F(\theta_s) = \frac{\pi L(\theta_s, \theta_v, \phi_v)}{R(\theta_s, \theta_v, \phi_v)}, \]  

where \( L(\theta_s, \theta_v, \phi_v) \) is the observed reflected SW radiance at the TOA at solar zenith angle \( \theta_s \), viewing zenith angle \( \theta_v \), and relative azimuth angle \( \phi_v \); \( R(\theta_s, \theta_v, \phi_v) \) is the anisotropic factor for the given geometry and scene type; and \( F(\theta_s) \) is the inferred flux. As noted in section 2, for GERB the relevant anisotropic factors are obtained from ADMs developed from observations made by the CERES TRMM instrument for specific scene types. However, at present no dedicated aerosol ADMs.
have been developed from this dataset. Instead, over
nominally clear ocean scenes, the CERES team ac-
count for the presence of aerosol through the following
adjustment:

$$F(\theta_s) = \frac{\pi L(\theta_s, \theta_v, \phi_r)}{R(\theta_s, \theta_v, \phi_r) \left[ R_{\text{th}}[L(\theta_s, \theta_v, \phi_r)] / R_{\text{th}}[L_{\text{ADM}}(\theta_s, \theta_v, \phi_r)] \right]} ,$$

(2)

FIG. 2. AERONET optical depths from the indicated coastal sites vs collocated GHR2 retrievals using (a) the Ignatov and Stowe aerosol model, (b) the Dubovik et al. dust aerosol model, and (c) the Hess et al. tropical maritime aerosol model for dusty days over the period April–June 2006. Details of the matching criteria are provided in the main text. For consistency AERONET optical depth measurements have been adjusted from a wavelength of 0.67 or 0.675 μm (dependent on site) to 0.63 μm using the relevant Ångström coefficient. In each case, the least squares linear fit is shown by the solid line and the one-to-one line is given by the dashed line for comparison.
where \( R_{th}(\theta_s, \theta_\sigma, \phi_\sigma) \) and \( R_{th}[L_{\text{ADM}}(\theta_s, \theta_\sigma, \phi_\sigma)] \) are theoretical anisotropic factors derived from lookup tables (LUTs) of simulated broadband radiances and fluxes as a function of AOD and wind speed. In this case \( L_{\text{ADM}}(\theta_s, \theta_\sigma, \phi_\sigma) \) is the radiance corresponding to the clear-sky ADM assigned to the given scene, and the anisotropic factor LUTs are developed using the Hess et al. tropical maritime aerosol model [see Loeb and Kato (2002) for full details]. In essence, the theoretical ratio in the denominator of Eq. (2) is a first-order attempt to quantify by how much the aerosol modifies the clear-sky anisotropic factors. The method is designed to provide a correction to the fluxes for scenes identified as “clear sky,” or essentially showing low aerosol contamination that does not get detected as cloud. The technique assumes that, within a given angular bin and outside the glint region, the flux is linearly related to the radiance. Given this approach, the question arises as to whether the method will work equally well for scenes that have been incorrectly classified as cloud and show heavy dust contamination. This question is addressed in section 4.

An alternative and perhaps more transparent way of determining fluxes would be to use an aerosol ADM directly, making use of collocated aerosol optical depth retrievals to effectively perform a scene identification. In this case,

\[
F(\theta_s) = \frac{\pi L(\theta_s, \theta_\sigma, \phi_\sigma)}{R(\tau, \theta_s, \theta_\sigma, \phi_\sigma)},
\]

where \( R(\tau, \theta_s, \theta_\sigma, \phi_\sigma) \) are anisotropic factors stratified according to AOD (\( \tau \)), \( \theta_s \), \( \theta_\sigma \), and \( \phi_\sigma \). In this case, \( R \) would ideally be based on observations of radiance anisotropy in the presence of dust. Although such information is beginning to be used to develop aerosol specific anisotropy models (Zhang et al. 2005a), at present these models are not sufficiently comprehensive for use here. Instead, Eq. (3) can be modified to

\[
F(\theta_s) = \frac{\pi L(\theta_s, \theta_\sigma, \phi_\sigma)}{R_{th}(\tau, \theta_s, \theta_\sigma, \phi_\sigma)},
\]

where \( R_{th}(\tau, \theta_s, \theta_\sigma, \phi_\sigma) \) are anisotropic factors derived from radiative transfer model calculations using an assumed aerosol model. This approach could be applied to any broadband radiance measurement and collocated AOD record but requires absolute accuracy in the retrieved AOD and the values of \( R_{th} \) for both clear and aerosol-contaminated scenes.

4. Testing theoretical aerosol ADMs and the radiance-to-flux conversion method

As noted in section 1, although the CERES TRMM ADMs are used to convert from radiance to flux, no attempt to allow for aerosol presence is performed within the GERB data processing. The aim in this section is thus twofold: 1) to establish which of the two methods represented by Eqs. (2) and (4) is more appropriate to perform GERB radiance-to-flux conversions in the presence of dust and 2) to assess whether the assumed aerosol type used in either approach significantly alters the reliability of the flux estimates. To perform this analysis, 3 months of GHR2 data, made up of ocean scenes from April to June 2006 observed between 0600 and 1800 UTC, were analyzed. For every 15-min time slot, observations that have a valid AOD limited by the retrieval algorithm to points with \( \theta_s < 70^\circ \), \( \theta_\sigma < 70^\circ \) (see Fig. 1), and glint angle \( \gamma > 40^\circ \) and that are identified by the dust detection algorithm as dusty were extracted. Comparisons with collocated MODIS cloud and aerosol flags presented in BR06 indicated that the dust detection scheme falsely identified cloud as dust in only 3% of the cases studied. However, in addition to the precautions described in BR06, to reduce further the possibility of including cloudy points that have been falsely flagged as dust, the maximum AOD of any given pixel was limited to 2.5.

The CERES TRMM ADMs were constructed by sorting observed instantaneous radiance observations into angular bins dependent on scene type (Loeb et al. 2003). The fixed viewing geometry available from GERB means that using a similar approach on the dusty points identified here will provide a limited angular coverage, insufficient to build a full dust ADM. Nevertheless, the observations can be used to test the realism of simulated aerosol ADMs at these angles by comparing observed radiances with theoretical values appropriate to the observation geometry and 0.63-\( \mu \)m AOD.

LUTs of broadband radiance as a function of \( \theta_s \), \( \theta_\sigma \), \( \phi_\sigma \), and AOD were constructed using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) radiative transfer code (Vermote et al. 1997a). The ocean surface was represented as the sum of contributions from sun glint, whitecaps, and the reflectance emerging from the seawater (Vermote et al. 1997b), assuming a surface wind speed of 7 m s\(^{-1}\). Two sets of LUTs were simulated, one appropriate to the Dubrovnik dust model, and one using the Hess tropical maritime aerosol representation. The calculations were performed at discrete angular intervals with solar and view zenith increments of 5° and relative azimuth increments of 10°. Then, for each observation of broad-

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1 Glint angle \( \gamma \) is given by \( \cos \gamma = \cos \theta_s \cos \theta_\sigma + \sin \theta_s \sin \theta_\sigma \cos \phi_\sigma \), where the angles are defined in the main text.
band radiance, the equivalent simulated radiance was obtained through the use of a Lagrangian minimization routine on each set of LUTs given AOD, θs, θo, and ϕr. Note that in both cases the AODs used in the retrieval process were appropriate to the given model used to derive the broadband LUT to avoid any inconsistency.

In addition, the radiances appropriate to the ADM applied in the GERB processing, \( L_{ADM}(\theta_s, \theta_o, \phi_r) \), were calculated using

\[
L_{ADM}(\theta_s, \theta_o, \phi_r) = [R(\theta_s, \theta_o, \phi_r)\alpha(\theta_s)\cos(\theta_s)F_s \cos(\theta_s)]/\pi,
\]

where \( \alpha(\theta_s) \) is the albedo at the observation solar zenith angle; \( F_s \) is the solar constant, taken to equal 1365 W m\(^{-2}\); and \( x \) is a factor to account for variations in the Earth–Sun distance.

Figure 3a shows a 2D histogram of the observed GHR2 radiance versus \( L_{ADM} \) for all of the dust-contaminated points identified using the criteria outlined above. Figures 3b and 3c show identical information for the observed versus derived Hess tropical maritime radiances and observed versus derived Dubovik dust radiances, respectively. Immediately apparent is the reduced scatter in Figs. 3b and 3c relative to Fig. 3a, suggesting that using either aerosol model in the radiance-to-flux conversion will result in more realistic dust fluxes than those currently contained in the GERB files. For the results obtained using the two aerosol representations, the Dubovik model gives a better overall agreement, with a root-mean-square error of 2.9 W m\(^{-2}\) sr\(^{-1}\) (8.1%) as compared with one of 3.6 W m\(^{-2}\) sr\(^{-1}\) (10.0%) obtained using the Hess model. Retrievals using both models tend to underestimate the observed radiance [biases of \(-2.4\) W m\(^{-2}\) sr\(^{-1}\) (–6.7%) and \(-3.2\) W m\(^{-2}\) sr\(^{-1}\) (–8.7%) for Dubovik and Hess, respectively]; however, note that these can be considerably reduced through the application of a multiplicative factor to the GHR2 radiances. For example, multiplying the observations by a factor of 0.95 reduces the biases to \(-1.1\) (–1.5) W m\(^{-2}\) sr\(^{-1}\) for the Dubovik (Hess) model. Such a factor is consistent with the overall level of agreement seen between colocated GERB ARG and CERES radiances (Dewitte et al. 2008).

Although the one-to-one level of agreement between the theoretical radiances and the observations is encouraging, an overall comparison can mask systematic differences that occur at specific observation geometries or aerosol loadings. More important, because the anisotropic factor required to convert a radiance to flux involves the ratio of the two quantities, and because the flux at a given solar zenith angle is by definition equal to the integral of the radiance over view and azimuth angles, the real constraint on using a particular representation is that it correctly reproduce the angular distribution of the observed radiances rather than their absolute value. In essence, if, for every solar zenith angle and AOD, the observed-to-retrieved radiance ratio shows little dependence on the viewing zenith and
relative azimuth angle, an ADM will give a realistic flux conversion regardless of the absolute value of the radiance ratio. Because we do not have a full set of geometries, we make the assumption here that if the ratio shows little variation over the sampled geometries then the previous statement still holds.

With this in mind, ratios of observed radiances to theoretical radiances were divided into eight AOD bins running from 0.0 to 1.0 in steps of 0.2, and then from 1.0 to 2.5 in steps of 0.5. Once binned, these ratios were further subdivided into 10° angular bins from 0° to 70° (solar/viewing zenith) and 0° to 180° (relative azimuth). Only the results from bins containing 20 or more points are retained. Figure 4 shows observed-to-theoretical radiance ratios as a function of viewing geometry for solar zeniths of 30°–40° across all eight AOD bins for the Dubovik aerosol representation. Identical information is provided in Fig. 5 for the Hess representation. In the ideal case, a perfect representation would give a flat surface of ratio of 1.0; however, recall that a perfect ADM only requires a flat surface of any ratio. In reality, both models show a degree of variation with viewing geometry in each bin. However, for all of the bins this variation is relatively small, with the Dubovik representation doing slightly better, with a standard deviation that is always less than 0.033. To summarize the results, Fig. 6a shows a contour plot of the standard deviation of the ratio as a function of θs and AOD bin for the Dubovik representation. Figure 6b indicates the number of observations from both models falling in each θs and AOD bin. Figure 6c shows the difference in ratio standard deviation across each bin between the Dubovik and Hess models. Although both models show relatively low variability in the ratio, the Dubovik dust model does show slightly reduced values across the vast majority of solar zenith and AOD bins (negative values in Fig. 6c). In particular, the Dubovik model offers an improvement in those bins that are most highly populated (cf. Fig. 6b with Fig. 6c). Note that we would not necessarily expect one aerosol model to be able to capture the complete range of behavior seen in the observations given changes in factors such as the mineralogy and size distribution associated with individual events (e.g., Sokolik and Toon 1999). Given this, the overall performance of the model gives confidence in its ability to capture generic dust behavior.

To allow full appreciation of the potential errors in the GHR2 fluxes in the presence of dust, Figs. 7a–d show the ratio of $L_{\text{ADM}}$ to observed GHR2 radiance for selected solar zenith and AOD bins. Here, observations are only selected if they have been converted using one specific ADM, equivalent to fully overcast conditions. As before, if the ADM captures the angular distribution of the radiance field well then the ratios should be relatively flat. For comparison, Figs. 7e–h show the ratios obtained using the same observations in conjunction with the Dubovik theoretical radiances. Much flatter ratios are seen when the observations are compared with the corresponding Dubovik radiances. These findings are replicated across the other solar zenith and AOD bins and for the other CERES ADM types applied to the GHR2 radiances. In essence, these results confirm that the theoretical Dubovik representation gives a much improved representation of the anisotropy contained within dusty ocean scenes over that of the ADMs currently employed in the GERB processing chain.

While it is clear that implementing a specific treatment for dust in the radiance-to-flux conversion will improve the quality of the GERB fluxes in dust-contaminated regions, it is less apparent which of the two approaches epitomized by Eqs. (2) and (4) will give a more reliable flux estimate. Equation (2) provides an adjustment to the anisotropic factor specific to the observed radiance. It does not provide an associated theoretical radiance; hence, comparisons that are similar to those illustrated in Figs. 3–7 cannot be performed. However, the corrected flux should, for a given scene at a given solar zenith angle, be independent of viewing geometry. Thus, if we bin fluxes derived using Eq. (2) as a function of AOD and solar zenith, then, if one assumes that our retrievals of AOD are a reliable indication of scene, these binned fluxes should show little dependence on view zenith and relative azimuth angle if the approach of Eq. (2) is robust. We hence apply Eq. (2) to the entire set of GHR2 radiances using the simulated Dubovik and Hess LUTs, and so derive corrected fluxes appropriate to each aerosol model. These are then binned according to the associated solar zenith angle and retrieved AOD. For ease of intercomparison, we also bin the fluxes derived from Eq. (4) in an identical manner. Figures 8a–d provide contour plots of the standard deviation in flux across view zenith and relative azimuth as a function of solar zenith and AOD bin for each flux derivation method using the Dubovik and Hess aerosol models. In this case the AOD ($\theta_s$) bin spacing is 0.1 (10°). As might be expected, the correction method (Figs. 8b,d) shows good flux consistency at low optical depths. However, for both aerosol models the variability increases with increasing AOD. Similar behavior is not seen when the appropriate theoretical ADM is applied directly to the observed radiances (Figs. 8a,c). In these cases, at a given solar zenith the flux variability stays at a relatively consistent level with AOD.
5. Quantification of GERB SW dust flux errors

a. Mean statistics

The results from the previous section would suggest that, out of the two radiance-to-flux conversion methods considered here, direct application of a suitable aerosol model [through Eq. (4)] will produce the most reliable means of converting GERB TOA SW radiances measured in the presence of dust to fluxes over the full range of observed dust loadings. Because the method depends on an AOD retrieval, for overall consistency it is also desirable that the selected aerosol model...
model provide good estimates of this quantity. Section 2 indicates that the Dubovik dust model can best fulfill this requirement. Given this, in this section the appropriate Dubovik model anisotropic factors are applied to the GHR2 radiances through Eq. (4) to provide an estimate of the “true” SW flux. For ease of reference, in the following sections we refer to this method as “Dubovik direct.” These values are then used to assess the error in the current GHR2 SW fluxes in the presence of dust aerosol.

Figure 9 provides an indication of the type of effect that might be expected for dusty points that are converted to flux using a clear ADM. Figure 9a shows the dependence of CERES TRMM anisotropic factors on
viewing zenith and relative azimuth angles for clear-sky
conditions for a solar zenith angle and wind speed bin
of 30°–40° and 5.5–7.5 m s⁻¹, respectively. For compari
son, simulated anisotropic factors for a range of dust
loadings, increasing from AOD = 0 (i.e., pristine con
ditions), using the broadband radiance and flux LUTs
derived with the Dubovik aerosol model are shown in
Figs. 9b–d. In each panel, the simulations have been
binned to match the angular resolution of the CERES
ADM and the 40° glint angle is marked by the solid
contour. The figure illustrates the role of an increas
ingly thick aerosol layer in reducing the anisotropy of
the scene. It also illustrates the problem associated with
using a clear-ocean ADM to convert an aerosol-
contaminated radiance to flux. Because the angular dis-
tribution of the aerosol radiances is more isotropic than
that for clear ocean, values of $R(\theta_s, \theta_v, \phi_v)$ at low glint
angles (inside the contour) will be larger for pristine
conditions than for aerosol-contaminated conditions,
with the converse being generally true at higher glint
angles (cf. Fig. 9b with Fig. 9d). Hence, from Eq. (1),
fluxes obtained using a clear-ocean ADM when aerosol
is actually present will be artificially inflated if the ra
diance observation is made outside the glint region and

Fig. 6. (a) Standard deviation of the ratio of the Dubovik theoretical radiance to observed
GHR2 radiance as a function of AOD and solar zenith angle, (b) the number of observations
in each AOD and solar zenith bin, and (c) the difference in the ratio standard deviation
between the Dubovik and Hess models. The zero contour is marked in black.
will be generally reduced if the radiance observation is made inside the glint region.

Figures 10 and 11 indicate the change in flux from the GHR2 value (defined in the sense of Dubovik direct flux–GHR2 flux) as a function of solar zenith and AOD, decomposed according to the ADM applied in the GERB processing. The vertical bars indicate the 1-σ spread in these differences within the given solar zenith and AOD bin. For clarity, only the six main ADM categories used over ocean are considered: be-

Fig. 7. (a)–(d) Angular distribution of the ratio of ADM radiance $L_{ADM}$ to observed radiance for selected solar zenith bins (optical depth bin is 0.6–0.8 in each case). (e)–(h) As in (a)–(d), but the ratios were obtained using the same observed radiances in conjunction with the Dubovik theoretical radiances.
 tween them, these constitute 89% of the observations. Table 1 provides details of the properties associated with each ADM that was considered.

For the cases in which the GERB cloud detection algorithm identifies the dusty scene as clear and applies a clear-ocean ADM (Figs. 10a–f), using the theoretical dust anisotropy factors reduces the flux across all but one of the filled AOD and θs bins. Such a pattern of behavior is as expected (see Fig. 9) because by definition all of the observations used here are outside the glint region. The magnitude of the difference is relatively insensitive to solar zenith angle but tends to increase with AOD, reaching a maximum reduction of \(-55 \text{ W m}^{-2}\) when the AOD is greater than 1.0 (Fig. 10a). Table 2 summarizes the mean difference averaged over solar zenith angle between the GHR2 and Dubovik direct fluxes for each of the clear-ocean ADMs, stratified by aerosol optical depth bin. The table also shows the number of points in each category. As expected, the majority of points identified as clear sky sit in the lowest AOD bins, and the overall mean difference, weighted by bin population is \(-12.2 \text{ W m}^{-2}\).

For dust-contaminated cases that the GERB cloud detection algorithm identifies as overcast (Figs. 11a–f), in general, applying the Dubovik direct method increases the flux over the GHR2 value, in particular in bins with the highest population of observations. There is, however, a slight tendency for the differences to become negative at low solar zenith angles (<10°) and when the solar zenith angle is 60° or more, so that the overall impact of applying the Dubovik direct method to these scenes is less clear-cut than for the cases that
the GERB processing treats as clear sky. This might be expected, because a cloud ADM will be more isotropic than clear ocean. Table 3 provides analogous information to Table 2 for the cases in which overcast ADMs are applied. In this case, the bin-weighted mean Dubovik direct–GHR2 flux difference is 1.0 W m$^{-2}$. Combining the clear and overcast differences and accounting for the number of observations in each case leads to a partial cancellation and an overall mean difference of $-2.5$ W m$^{-2}$.

b. Impact on temporally resolved fluxes

Although the previous section implies that the overall effect of applying the Dubovik direct method is small for the period considered here, Figs. 10 and 11 clearly show that large errors are present in the GHR2 fluxes if the observations are decomposed according to measurement geometry and AOD. To emphasize this point further, we revisit the AERONET comparisons of section 2 but highlight the effect of employing the Dubovik direct method on temporally resolved observations from GERB over selected sites. Figure 12a shows the AERONET AOD through 23 May 2006 over the Bahrain site, binned into 15-min intervals. Also plotted are the mean Dubovik AOD retrievals from within $0.5^\circ$ of the site, obtained using matching criteria that are identical to those of section 2, and the vertical error bars show the spatial variability in these values. Figure 12b shows both GHR2 fluxes and the corresponding Dubovik direct fluxes. An indication of whether the GERB scene ID selected a clear, cloudy, or mixed ADM is also provided. Again, the vertical
error bars indicate the 1-σ spatial variability in fluxes. In Fig. 12a, the Dubovik retrievals are generally within 0.1 of their AERONET counterparts throughout the day, and both records show a reduction in AOD magnitude over the course of the day. In this case, the aerosol loading is fairly high throughout the day and the GERB scene ID classifies the scenes as predominantly cloudy. However, although the scene ID is constant, the changing observation geometry translates to a time-varying difference between the GHR2 and Dubovik direct fluxes ranging from $-27$ to $9 \, \text{W m}^{-2}$ (Fig. 12b). Overall, the tendency is for the Dubovik direct fluxes to show less temporal variation than their GHR2 counterparts.

An identical plot is provided for the Blida, Algeria, site on 25 June 2006 (Fig. 13). Here the GHR2 dust
loadings decrease through the morning and stay constant through the early afternoon before increasing slightly toward late afternoon (Fig. 13a). Periods of higher loadings correspond to the GERB scene ID classifying the observations as cloudy, whereas for intermediate and lower loadings the scene is classified as mixed and clear, respectively (Fig. 13b). For this case the Dubovik fluxes are always lower than their GHR2 counterparts, and there is an obvious tendency for the cloudy scenes to show the largest flux differences of up to 32 W m$^{-2}$. Again, the Dubovik direct fluxes show much less variability than the GHR2 values. In addition, from 1400 UTC onward, the time-varying behavior of the Dubovik direct fluxes is actually in the opposite sense to the GHR2 values.

In Fig. 14, the effect of a change in scene ID over the Forth_Crete, Greece, site on 18 April 2006 from mixed through clear to cloudy conditions is considered. In this case, the dust loading is relatively constant throughout the day (Fig. 14a), with the Dubovik retrievals consis-
tently lower than the AERONET values by ~0.1. Here, the GHR2 and Dubovik direct fluxes show good agreement when the scene ID shows a mixture of clear and cloudy conditions. However, when one scene type dominates, the records begin to diverge, with the amplitude of the diurnal variation in flux being reduced when the Dubovik direct method is applied to the GERB radiances. In essence, then, the use of GHR2 (and by extension GERB ARG) fluxes in dusty conditions will not only misrepresent the overall solar energy available at a particular location, but is also likely to incorrectly capture the evolution of that energy with time.

c. Radiative effect efficiency

Because the application of the Dubovik direct method to GHR2 radiances produces markedly different fluxes, in this section the corresponding effect on the instantaneous dust radiative efficiency (DREF) is calculated. We make the distinction from the commonly used radiative forcing efficiency term because we are focusing on mineral dust aerosol, which has predominantly natural sources. For consistency with previous studies of the instantaneous efficiency, in this section observations are limited to ocean regions within 10°–30°N and 10°–60°W and a maximum solar zenith angle of 60°. The geographical area is consistent with the North Atlantic zone studied by Zhang et al. (2005b). Although Zhang et al. do not distinguish among different aerosol types in calculating DREF, for the late spring and summer months considered here aerosol loading in this region should be dominated by dust outbreaks (e.g., Yu et al. 2006).

Figure 15a provides an indication of the dependence of the GHR2 TOA SW fluxes on the retrieved AOD averaged over all solar zenith angle bins. The fluxes shown are means taken over 0.02-AOD-wide bins up to the maximum AOD of 2.5, with the proviso that at least 500 observations must exist in a given bin for the average to be made. The standard deviation within each bin is shown by the vertical error bar. The figure shows a clear transition from the regime in which fluxes are determined using predominantly clear ADMs (AODs generally less than 0.35) to the regime in which cloudy ADMs are applied (AODs generally greater than 0.5). At intermediate AODs, the two different regimes result in larger standard deviations and a flattening of the rate of change of flux with AOD, which would appear to be unphysical.

The corresponding Dubovik direct fluxes are indicated in Fig. 15b. The application of one ADM over the entire AOD range results in a consistent pattern of behavior, with a clear departure from linearity for AODs in excess of ~1.2. Applying a linear fit over the AOD range 0.0–1.2 inclusive yields the fit shown by the dashed line in Fig. 15b. Defining DREF as the rate of change in reflected TOA SW flux per unit increase in AOD or the gradient of the linear fit (e.g., Zhang et al. 2005a) results in a value of 78 ± 3 W m⁻² τ⁻¹. This figure is broadly consistent with the estimates of ~70 W m⁻² τ⁻¹ obtained by Zhang et al. (2005b) over the same region during March–August 2001.

6. Conclusions and discussion

In this paper, we have sought to identify a way of assessing the quality of GERB SW fluxes in the presence of aerosol given that the current GERB process-

| Table 1. Description of the CERES TRMM ADM categories highlighted in Figs. 10 and 11. |
|-----------------------------------------|-----------------|-------------------|
| ADM | Conditions | Surface wind speed (m s⁻¹) | Cloud optical depth |
| 2 | Clear | 3.5–5.5 | — |
| 3 | Clear | 5.5–7.5 | — |
| 4 | Clear | >7.5 | — |
| 169 | 99.9%–100% cloud fraction | — | 0.01–1.0 |
| 170 | 99.9%–100% cloud fraction | — | 1.0–2.5 |
| 171 | 99.9%–100% cloud fraction | — | 2.5–5.0 |

| Table 2. Dubovik direct minus GHR2 SW TOA clear-sky flux differences Δ (W m⁻²) as a function of ADM and AOD bin. The number of observations n used to form the average in each bin is also shown. “Total” differences are weighted according to bin population. |
|-----------------------------------------|-----------------|-------------------|
| ADM | n | Δ | n | Δ | n | Δ | n | Δ | n | Δ |
| 2 | 51 311 | −10.2 | 100 403 | −17.5 | 47 821 | −28.8 | 1376 | −29.2 | 811 | −37.0 |
| 3 | 431 772 | −7.1 | 176 612 | −17.9 | 37 082 | −27.5 | 1744 | −28.2 | 740 | −38.1 |
| 4 | 137 367 | −4.8 | 183 615 | −13.7 | 30 167 | −14.0 | 520 | −3.7 | — | — |
| Total | 620 450 | −6.8 | 460 630 | −16.1 | 115 070 | −24.5 | 3640 | −25.1 | 1551 | −37.5 |

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ing does not account for the effect of aerosol on the anisotropy of a scene when converting from radiance to flux. We have focused on dust-contaminated conditions over a 3-month period from April to June of 2006. From these data, we have

1) built on previous studies (e.g., BI06) to assess further the quality of dust AOD retrievals in the GERB product and those obtained using alternative aerosol representations more suited to the application here,

<table>
<thead>
<tr>
<th>ADM</th>
<th>AOD bin</th>
<th>n</th>
<th>Δ</th>
<th>n</th>
<th>Δ</th>
<th>n</th>
<th>Δ</th>
<th>n</th>
<th>Δ</th>
<th>n</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>169</td>
<td>0.0–0.2</td>
<td>5328</td>
<td>−5.4</td>
<td>120 088</td>
<td>−3.2</td>
<td>827 001</td>
<td>3.0</td>
<td>191 857</td>
<td>−2.5</td>
<td>3006</td>
<td>−2.4</td>
</tr>
<tr>
<td>170</td>
<td>0.2–0.4</td>
<td>2318</td>
<td>−2.6</td>
<td>57 347</td>
<td>−0.3</td>
<td>338 913</td>
<td>−2.9</td>
<td>756 169</td>
<td>4.2</td>
<td>453 833</td>
<td>1.2</td>
</tr>
<tr>
<td>171</td>
<td>0.4–0.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3184</td>
<td>1.0</td>
<td>27 108</td>
<td>1.1</td>
<td>49 526</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>7646</td>
<td>−4.6</td>
<td>177 435</td>
<td>−2.3</td>
<td>1 169 098</td>
<td>1.3</td>
<td>975 134</td>
<td>2.8</td>
<td>497 424</td>
<td>1.1</td>
<td>102 568</td>
</tr>
</tbody>
</table>

Fig. 12. (a) Temporal evolution of AERONET aerosol optical depths through 23 May 2006 at the Bahrain site, binned into 15-min intervals. Mean GHR2 retrievals for points within a ±0.5° lat/lon radius of the site are overplotted. (b) Corresponding evolution of GHR2 SW fluxes (GHR2). Fluxes derived from the GHR2 radiances using the Dubovik anisotropic factors are also shown (Dubovik). An indication of whether the scene was identified as clear, cloudy, or mixed is provided. In both (a) and (b), the vertical error bars indicate the spatial variability in the relevant GHR2 product.
2) assessed whether the representations introduced in step 1 are also capable of matching the angular distribution of broadband GERB radiances measured in the presence of dust,

3) identified a suitable method for converting radiance to flux given the results of steps 1 and 2 and currently available tools, and

4) applied this method to quantify the likely error in GERB SW fluxes derived in the presence of dust aerosol.

The additional AOD retrievals performed here used the same retrieval algorithm as that implemented in the GERB product but employed alternative aerosol representations. The first of these, from Dubovik et al., was derived from ground-based observations of dust events; the second, from Hess et al., is characteristic of tropical maritime aerosol and has been used historically by the CERES team to obtain TOA broadband SW fluxes in the presence of aerosol. Comparisons with collocated AERONET observations over the period considered here indicate that AOD retrievals obtained using the Dubovik dust representation best match the ground-based measurements, with a correlation coefficient of 0.84. Retrievals using the generic Ignatov and Stowe aerosol representation, designed specifically to optimize narrowband retrievals over ocean and used operationally to obtain the GERB AOD fields, show a similar level of agreement. However, retrievals using the Hess tropical maritime representation show a larger scatter, with the correlation coefficient dropping to 0.72.

The ability of the Dubovik and Hess models to match the angular distribution of broadband radiance in the presence of dust was then tested through the comparison of GHR2 radiances with values extracted from...
LUTs built using the two representations. For completeness, the radiances appropriate to the applied ADMs used in the radiance-to-flux conversion of the same set of GHR2 observations were also calculated. These comparisons show that both the Dubovik and Hess models are able to replicate the observations better than can the derived ADM values. Perhaps more important in terms of a radiance-to-flux conversion, for both models the quality of the match seen for given AOD and solar zenith angle bins shows little dependence on viewing zenith and relative azimuth angle. Overall, use of the Dubovik model results in both the best match to the entire radiance set [rms differences of 2.9 W m\(^{-2}\) sr\(^{-1}\) (8.1%), bias of \(-2.4\) W m\(^{-2}\) sr\(^{-1}\) (\(-6.7\%\)) and the lowest level of angular variability over the vast majority of AOD and solar zenith bins (44 out of 56 bins).

On initial analysis it may seem counterintuitive that the larger scatter seen in the AOD comparisons using the Hess model is not fully translated to the broadband comparisons. A small part of this apparent dichotomy is due to compensating effects between the model behavior in the narrow spectral region used in the AOD retrievals and that seen over the full spectrum included in the broadband integration. However, the fractional contribution of the 0.6-μm channel to the total broadband radiance does not alter significantly between the two models, and the main compensation arises because of the use of a consistent model to derive both AOD and broadband radiance. As noted above, the Dubovik model gives better overall agreement with collocated AERONET observations than does the Hess representation. If, at a given geometry, the Hess model shows a lower (higher) 0.6-μm channel radiance than Dubovik, it will translate into a higher (lower) AOD retrieval. Using the higher (lower) Hess AOD to obtain the
broadband radiance will result in a higher (lower) value than would have been the case if the more realistic Dubovik AOD had been used to derive the Hess broadband value. Hence, much of the scatter seen in the AOD comparisons is reduced when comparing the broadband radiances. In summary, a truly representative model should show both good AOD and broadband agreement.

Two methods that could be used to convert radiances to fluxes in the presence of aerosol have been assessed here. The first, from Loeb and Kato, is used operationally in the CERES processing and essentially corrects nominally clear-sky anisotropic factors to account for the effects of aerosol. The second involves the direct application of theoretical anisotropic factors derived from simulated aerosol broadband radiance and flux LUTs. The viability of each method is assessed by comparing the variation of the fluxes derived in each case with relative azimuth and viewing zenith angle for specific solar zenith angle and AOD bins. By definition, for a given solar zenith and AOD, flux should show no dependence on relative azimuth or viewing zenith. In practice, because we are considering binned quantities some variability is expected, but this underlying varia-

![Diagram](http://journals.ametsoc.org/jamc/article-pdf/47/6/1659/3543033/2007jamc1723_1.pdf)
tion will be augmented by a method’s inability to represent correctly the angular distribution of the radiance field. Whereas the fluxes derived using the direct application approach show relatively low, consistent variability with solar zenith and AOD, we find that fluxes obtained using the correction approach tend to show a systematic increase in variability as AOD increases. We suggest that this result implies that the correction approach is a less reliable conversion method at higher AODs (in excess of ~1.0). The method by which the correction factor in Eq. (2) is calculated implicitly assumes that, within a given angular bin and outside the glint region, broadband flux varies linearly with broadband radiance (N. Loeb 2006, personal communication). Although this condition holds at low AODs, it tends to break down at the higher values sampled here.

Given the ability of the Dubovik dust model best to capture the AOD field and the broadband radiance field for the cases studied here, this representation was used in conjunction with the direct application method to derive broadband TOA SW fluxes from the observed GHR2 radiances. These “Dubovik direct” values were then compared with the original GHR2 fluxes to obtain a measure of the error in the GHR2 values in the presence of dust. Over the entire ensemble of observations, the difference between the Dubovik direct and GHR2 fluxes was small at ~2.5 W m$^{-2}$. However, decomposing these results as a function of GERB scene ID and dust loading illustrates the potential bias introduced by neglecting the dust impact on the scene anisotropy. For scenes identified by the GERB processing as clear, applying the Dubovik direct method to determine the flux reduced the reflected SW flux by an average of ~12 W m$^{-2}$. For scenes identified by the processing as cloudy, the mean effect of using the Dubovik direct method was an enhancement of 1 W m$^{-2}$. More significant is that the magnitude of the effect was seen to vary between 0 and 55 W m$^{-2}$ depending on the solar geometry, scene ID, and dust optical depth. Because of this, the temporal evolution of the reflected GHR2 and Dubovik direct fluxes at particular locations can be significantly different or even inverted. This fact has serious implications for the use of GHR2 SW fluxes as they stand in energy balance studies over dust-contaminated ocean scenes. Furthermore, attempting to derive the direct radiative effect efficiency of dust from the GERB data as it stands will produce spurious results because of the tendency for scenes showing low AOD loadings to have their associated radiance converted using a clear ADM and scenes with higher AOD loadings to be converted using a cloud ADM. The former tend to show a larger rate of change of flux with AOD relative to the latter, which results in unphysical behavior in the cross-over region between the two regimes. Applying the dust direct conversion method to the GHR2 radiances produces consistent fluxes over the entire AOD range, with an associated instantaneous direct radiative effect efficiency over the North Atlantic region of 78 ± 3 W m$^{-2}$ τ$^{-1}$.

Given the results of this study, we recommend that a specific aerosol treatment is highly desirable in future editions of the GERB data. Although we have focused on dust aerosol here, we would expect errors also to be present for scenes contaminated by other aerosol types, in particular those that can exhibit high loadings. A particularly pertinent example would be biomass-burning events that extend over the western Atlantic. As a first correction, a CERES-like approach would improve matters over the existing GERB processing for low aerosol loadings (AOD < ~1.0) identified as clear sky. As an alternative, assuming a sufficient sample size, the method outlined here could be employed to test theoretical ADMs developed for other generic aerosol types. Such an approach is not limited to GERB but could also be used with any set of collocated AOD and broadband radiance observations.

Last, we acknowledge that we have reported the results for only one dust model, but we note that preliminary analysis of alternative representations (e.g., that of Hess et al. 1998) indicated unrealistic broadband radiance behavior, similar to a previous study (B106). We also note that any treatment scheme must be consistent with the capabilities of the operational GERB AOD product and sufficiently fast to be incorporated in the near-real-time GERB processing system. We anticipate that using the approach developed here in conjunction with the evolving GERB radiance record will eventually enable us to fully quantify the impact of dust aerosol on the earth’s radiative energy balance on time scales ranging from minutes to years.

**Acknowledgments.** We thank our colleagues at RMIB for supplying the GERB HR L2 data, Oleg Dubovik for providing the nonspherical dust model optical properties, NASA for providing access to the MODIS data, and Didier Tanré, Brent Holben, Lucas Alados Arboledas, Manolis Drakakis, and their staff for establishing and maintaining the five AERONET sites used in this investigation. We also thank Norman Loeb for his helpful comments concerning the implementation of the CERES aerosol correction method. We also acknowledge the insightful comments of several anonymous reviewers that helped to improve this manuscript. HEB is funded by the Natural Environment Research Council, United Kingdom, under Grant NE/D009197/1.
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