ESTIMATING THE IMPACT OF AEROSOL ON RADIATIVE FLUXES OBTAINED FROM THE GEOSTATIONARY EARTH RADIATION BUDGET (GERB) INSTRUMENT

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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 diurnally resolved evolution of the top of atmosphere broad-band radiation fields. Edition 1 GERB climate quality products have recently been released to the scientific community, and, in addition to the observed radiances and inferred fluxes, also include information concerning the aerosol field sampled by the instrument. However, as yet, no dedicated scheme to account for the anisotropic characteristics of aerosol has been incorporated in the short-wave radiance to flux conversion methodology, which instead uses anisotropic factors from angular distribution models developed for clear or cloudy conditions. Here we attempt to quantify the impact of this omission, focussing specifically on the North Atlantic Ocean (10°-30°N, 10°-60°W) through spring 2006. Using Edition 1 GERB fluxes as they stand, the three month regional mean TOA instantaneous short-wave aerosol direct radiative effect efficiency in cloud-free conditions is ~86 W m⁻² per unit aerosol optical depth. Accounting for the effect of aerosol on the anisotropy of a given scene reduces this value to ~75 W m⁻² per unit aerosol optical depth, a value which shows greater consistency with previous estimates made using observations from instruments in polar orbit.

1. INTRODUCTION

The potential for dust aerosol to strongly modify the components of the Earth’s radiation balance has been recognised for some time (e.g. Ackerman and Chung, 1992). In-situ aircraft observations indicate that in the presence of heavy Saharan dust loadings the reflected short-wave (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 based on 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 satellite suggest an instantaneous aerosol direct radiative forcing efficiency of ~70 W m⁻² per unit aerosol optical depth over the North Atlantic Ocean during the spring and summer months (Zhang et al., 2005), a region and time period when aerosol loading is dominated by Saharan dust outflow from the African continent (Yu et al., 2006).

Broadband radiance and flux products from the Geostationary Earth Radiation Budget (GERB) instrument (Harries et al., 2005) flying on Meteosat-8 have recently been released for analysis by the scientific community. Because of the satellite’s geostationary location at 0°N, 3.5°W, GERB has an excellent view of the African continent, the Atlantic Ocean and the Mediterranean Ocean. The instrument’s spatial resolution of ~50 km (at nadir) and temporal resolution of ~15 minutes, and its synergy with narrowband information available from the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) instrument (Schmetz et al., 2002) means that GERB can monitor the direct radiative effect of aerosol events such as Saharan dust storms as they evolve in time throughout the day. However, while algorithms to both detect dust over ocean and to quantify the amount of aerosol present using SEVIRI have been developed and are contained within the GERB products, the results do not affect the SW radiance to flux conversion. Instead, the 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 onboard the Tropical Rainfall Monitoring 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, particularly 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 due to the highly anisotropic nature of ocean scenes.

Recent work by Brindley and Russell (2007) showed that while the technique introduced by Loeb and Kato (2002) to correct for aerosol anisotropy in a SW radiance to flux conversion performs adequately for low to moderate dust aerosol loadings (aerosol optical depth (AOD) < ~1.0), at higher AODs the assumption of a linear relationship between radiance and flux used in the correction procedure tends to break down. Instead, they developed a dust specific angular distribution model derived from radiative transfer model simulations using a dust representation based on sun-photometer observations (Dubovik et al., 2002). In this paper we initially obtain aerosol direct radiative effect estimates using the GERB Edition 1 fluxes as they stand, and then use a combination of the two correction approaches to derive an estimate which explicitly accounts for aerosol anisotropy in the radiance to flux conversion methodology. By comparing the two results we provide estimates of the likely error that will result from neglecting aerosol anisotropy when calculating both the aerosol direct radiative effect and efficiency.

With this aim, in section 2 we describe 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 standard aerosol model used in the GERB processing. In section 3 we introduce the approach used here to perform a radiance to flux conversion in the presence of aerosol while in section 4 we employ this method to quantify the impact of neglecting the effect of aerosol on the GERB SW fluxes and derived aerosol direct radiative effect and efficiency. Conclusions from this study are provided in section 5.

2. GERB PRODUCTS

A detailed description of the GERB instrument, including an outline of the data processing chain and data archival arrangements are provided in Harries et al. (2005). GERB Averaged, Rectified and Geolocated (ARG) level 2 products were released for use by the scientific community on May 11th 2006 and can be accessed from the GERB Ground Segment Processing System (http://ggspslrl.ac.uk). Here we use GERB High Resolution (HR) level 2 shortwave radiances and associated fluxes, contained within the GERB HR level 2 product (hereafter GHR2) for the period March to May 2006. GHR2 products use 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 x 50 km at nadir) to a 3x3 SEVIRI pixel resolution (~10 x 10 km at nadir) (Dewitte et al., 2007). As part of the GERB processing, SW fluxes are determined from the radiances by the application of the appropriate CERES TRMM ADMs chosen according to the GERB scene 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 Brindley and Russell (2006), and three AOD fields corresponding to the solar reflectance bands on SEVIRI. Both are provided over ocean only, the AOD fields being produced using an algorithm developed initially for the Advanced High Resolution Radiometer (AVHRR) and subsequently adapted for SEVIRI (Brindley and Ignatov, 2006). Details of the performance of the AOD retrievals made in dusty conditions are provided for selected case studies in the latter paper. For these cases, retrievals performed using the AVHRR generic aerosol model (used operationally in GERB products) showed very good agreement with matched MODIS and cloud screened AERONET (Holben et al., 1998) observations. Nevertheless, to provide a more extensive test of the quality of the AOD retrievals, comparisons over the
period analysed here are presented over the Dakar AERONET site situated at 14.39°N, 16.96°W. Figure 1(a) shows a scatter plot of AOD at 0.63 μm as obtained from the AERONET site against coincident GHR2 retrievals. Temporal and spatial matching is achieved by constraining the retrievals to be within ± 7.5 minutes and ± 0.5° of the AERONET measurements. Two further quality controls are imposed: first, to avoid the possibility of coastal contamination, only retrievals situated greater than one HR pixel away from a land point are retained when forming the spatial averages; second, to remove cloudy pixels which have been falsely identified as aerosol contaminated, the standard deviation of the broad-band 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 between achieving the removal of obviously cloudy points, while retaining the vast majority of AOD retrievals. In each plot the vertical error bars in indicate the 1-spread due to the spatial averaging employed. For the three months considered here the level of agreement is good, with an overall rms difference of < 0.1 and a mean bias of ~ 0.02.

![AERONET AOD versus co-located SEVIRI retrieved AOD at 0.63 μm for all available time-slots at the Dakar AERONET site through April, May and March 2006. Vertical bars show the spatial standard deviation in the SEVIRI averages. The one-to-one line is shown as dashed. Mean biases and root-mean-square differences for each month are also provided.](image)

Figure 1: AERONET AOD versus co-located SEVIRI retrieved AOD at 0.63 μm for all available time-slots at the Dakar AERONET site through April, May and March 2006. Vertical bars show the spatial standard deviation in the SEVIRI averages. The one-to-one line is shown as dashed. Mean biases and root-mean-square differences for each month are also provided.

Figure 2 shows monthly mean ‘cloud-free’ instantaneous AOD maps for an area centred on the North Atlantic region (10-30°N, 60-10°W). This region is chosen to allow comparison with previous work by Zhang et al., (2005) performed for spring 2001. The general pattern of aerosol loading is consistent with this earlier work, although the overall three month mean value is somewhat higher, 0.23 compared to 0.12, possibly reflecting inter-annual variability in dust transport over the region. Note also that the latter value is derived at a wavelength of 0.55 μm as opposed to the 0.63 μm SEVIRI AOD, which might be expected to slightly reduce the difference seen. AOD values in March 2006 are particularly high (regional monthly mean value of 0.33 compared to 0.19 and 0.17 in April and May respectively), a direct consequence of the outflow of a large Saharan dust storm out over the North Atlantic through 8-13th March (see Slingo et al., 2006).
3. RADIANCE TO FLUX CONVERSION METHODOLOGY

A schematic of the method used here to convert SW radiances to fluxes is provided in Figure 3. AOD retrievals are performed routinely on pixels designated ‘clear’ or ‘dusty’. Radiances, \( L \), from ‘clear’ pixels are converted to flux, \( F \), using:

\[
F(\theta_s) = \frac{\pi XL(\theta_s, \theta_v, \phi_r)}{R(\theta_s, \theta_v, \phi_r) [R_{th}(L(\theta_s, \theta_v, \phi_r))]} \tag{1}
\]

where \( R_{th}(L(\theta_s, \theta_v, \phi_r)) \) and \( R(\theta_s, \theta_v, \phi_r) \) are theoretical anisotropic factors derived from look up tables of simulated broad-band radiances and fluxes as a function of AOD and wind-speed, and \( \theta_s, \theta_v \) and \( \phi_r \) are the solar zenith, view zenith and relative azimuth angles respectively. \( L_{ADM}(\theta_s, \theta_v, \phi_r) \) is the radiance corresponding to the clear-sky ADM assigned to the given scene, with associated anisotropic factors, \( R(\theta_s, \theta_v, \phi_r) \). Essentially the theoretical ratio in the denominator of equation (1) is a first order attempt to quantify by how much the aerosol modifies these clear-sky anisotropic factors (see Loeb and Kato, 2002 for full details).

For pixels identified as ‘dusty’, the following conversion is used:

\[
F(\theta_s) = \frac{\pi XL(\theta_s, \theta_v, \phi_r)}{R_{DUST}(\theta_s, \theta_v, \phi_r)} \tag{2}
\]

where \( R_{DUST}(\theta_s, \theta_v, \phi_r) \) are anisotropic factors taken from a theoretical ADM developed specifically for dust aerosol (Brindley and Russell, 2007). Over a three month period, radiances extracted from this ADM for a given retrieved AOD and geometry were found to agree with the corresponding observed GERB radiances to within \( \pm 8 \% \) (2.9 W m\(^{-2}\) sr\(^{-1}\)).
4. AEROSOL DIRECT RADIATIVE EFFECT

The SW aerosol direct radiative effect, DRE, is defined as:

\[ \text{DRE} = F(\theta_s)p - F(\theta_s) \]  

Where \( F(\theta_s) \) is the SW flux obtained from the observed GERB radiances using the method outlined in section 3, and \( F(\theta_s)p \) is the pristine-sky SW flux at the given solar zenith angle. Pristine-sky fluxes are estimated from the y-intercept of a linear fit of the GERB fluxes versus AOD performed for each 1° bin in solar zenith angle, analogous to the approach used by Loeb and Kato (2002). Figure 4 shows the monthly mean cloud-free instantaneous DRE calculated from equation (3) for March, April and May 2006. Unsurprisingly the distributions closely follow the AOD maps shown in figure 2, with the DREs seen in March being, on average, a factor of two greater than those in the following two months. The three month regional mean DRE is \(-17.2 \text{ W m}^{-2}\), which compares to the value of \(-8.5 \text{ W m}^{-2}\) obtained by Zhang et al. (2005) over the same region and period during 2001. Scaling these values by the three month regional mean AODs given in section 2 should account for the influence of the change in aerosol loading between the two years while effectively providing a first order estimate of the instantaneous aerosol SW DRE efficiency. Values for the SW DRE efficiency are hence \(-74.8 \text{ W m}^{-2} \text{ per unit AOD}\) using GERB fluxes derived in the manner described in this study, as compared to \(-70.8 \text{ W m}^{-2} \text{ per unit AOD}\) from Zhang et al.. Recall that the latter study uses AODs reported at 0.55 \( \mu \text{m} \), which would likely act to slightly reduce the SW DRE efficiency relative to a value calculated with a 0.63 \( \mu \text{m} \) AOD.

Finally, it should be noted that the corresponding three month regional mean SW DRE calculated from Edition 1 GERB fluxes as they stand (without accounting for aerosol in the radiance to flux conversion) is \(-20.0 \text{ W m}^{-2}\), which would translate to an efficiency of \(-86.0 \text{ W m}^{-2} \text{ per unit AOD}\). This inflated magnitude is consistent with the expectation that in general aerosol contaminated Edition 1 fluxes are likely to have been identified as clear (low background AODs) and hence converted with an unrealistically low anisotropic factor (see Brindley and Russell, 2007). Although the overall difference in DRE might appear fairly small, monthly mean estimates of SW DRE using fluxes derived with the approach outlined here and those contained in the Edition 1 release range can differ by between \(-40 \text{ and } +9 \text{ W m}^{-2}\) dependent on location and month.
5. CONCLUSIONS

In this study we have outlined a method to convert SW radiance to flux in the presence of aerosol. We apply the method to GERB Edition 1 radiances, in order to ascertain the impact of not explicitly accounting for aerosol in the radiance to flux conversion process, focusing specifically on the North Atlantic region during spring 2006.

Aerosol optical depths (AOD) derived from SEVIRI and contained within the GERB Edition 1 product show good consistency with co-located AERONET observations over the period considered. In comparison with a previous study, the spring regional mean aerosol loading during 2006 appears relatively high, mainly due to inflated values in March occurring as a result of transport out over the ocean from a major Saharan dust storm.

Corresponding estimates of the SW direct radiative effect (DRE) using the methodology outlined here ('aerosol corrected') give a spring regional mean value which is approximately 3 W m$^{-2}$ smaller than that which would be obtained from the GERB Edition 1 SW fluxes as released to the scientific community. Decomposing this value according to month and location revealed that the discrepancies could reach a figure as high as 40 W m$^{-2}$ in the monthly mean. Scaling the spring regional mean GERB Edition 1 DRE value by the corresponding AOD gave a DRE efficiency of 86 W m$^{-2}$ per unit AOD. This value is markedly higher than a previous independent estimate over the same region and season, which is of the order 71 W m$^{-2}$ per unit AOD. Much greater consistency is seen for the aerosol corrected SW DRE, with an efficiency of ~75 W m$^{-2}$ per unit AOD, giving confidence in the flux derivation procedure.

Given these findings we strongly advocate that the GERB Edition 1 SW fluxes as they stand should not be used to evaluate aerosol radiative impacts. The results obtained using the methodology outlined here to account for aerosol anisotropy in the radiance to flux conversion process suggest that the technique may be a useful candidate for inclusion when re-processing the GERB data to create future edition releases.
REFERENCES


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