ABSTRACT

In principle, when the angular distribution of the energy is known it is possible to estimate instantaneous flux at the Top Of the Atmosphere (TOA) in any viewing geometry. Nevertheless due to the coarse angular bins resolution used to define Angular Distribution Models (ADMs) clear sky TOA Short Wave (SW) flux retrievals are unreliable for footprints near the specular reflection direction. Consequently, radiance-to-flux conversion is generally not performed in the sun glint regions. However, ignoring these samples (e.g., by not providing a TOA flux estimate) can introduce biases in regional mean fluxes because fluxes over cloudy portions of a region will contribute disproportionately to the overall regional mean. By combining the high temporal sampling of the sun glint regions afforded by geostationary orbit with information contained in clear ocean SW ADMs we show that an improved estimation of the reflected SW flux at TOA is possible.

Moreover, along the coastlines of continents, scenes which are a mix of two or more types (e.g., ocean and land, land and desert) occur. Since data used to build ADMs were generally not sorted for mixed-scene type, instantaneous SW TOA flux is determined using the ADM that corresponds to the surface type with the highest percent coverage over the footprint when a footprint contains a mixture of surface types. As an example, near coastlines, if most of the footprint point spread function-weighted area is over ocean, an ocean ADM is used to convert the radiance to flux. In converse, if most of the footprint area is over land, one of the land ADMs is used. However, due to the large anisotropy difference which exists between ocean and land ADMs this leads to generate large discontinuities in the retrieved fluxes over coastlines regions. Strategy is given here to correct such a bias in the reflected SW flux estimation at the TOA.

1. INTRODUCTION

Because satellite radiometers do not measure the instantaneous reflected SW flux at TOA directly, ADMs are required to relate the actual radiance measurement to flux at given solar angle, satellite-viewing geometries, and surface and atmospheric conditions. Considering the newly developed CERES-TRMM broadband (BB) SW ADMs (Loeb et al., 2003) we have investigated if the associated anisotropic correction factors allow to satisfactorily retrieve the reflected clear-sky SW fluxes at TOA when radiance measurements are contaminated by sun glint. While CERES-TRMM ADMs represent a major advance over previous ADMs regarding the number of available ADM scene types but also in terms of angular resolution, no mixed surfaces scene types have been derived when building these ADMs. Because changes in the physical and optical properties of a scene have a strong influence on the anisotropy of the radiation at TOA we have also investigated if ignoring the modifications in the anisotropy of surface-leaving radiances could result in systematic TOA flux errors over footprints containing a mixture of scene types.

In the absence of reliable GERB data at this time we have considered clear sky SW fluxes retrieved from Meteosat-7 (MS-7) data as surrogate for the forthcoming GERB SW fluxes.

2. REFLECTED TOA CLEAR SKY GERB-LIKE SW FLUX COMPUTATION

Due to the only raw estimate of the visible channel calibration provided by Eumetsat, a cross-calibration of the MS-7 visible channel is performed according to the well-calibrated SW channel of the CERES instrument.
Then, the total SW radiance is estimated from the visible filtered measurements using a third degree regression on the filtered measurements. The regression coefficients are obtained by least mean square minimization on a database of spectral radiance curves. Finally, after a preliminary scene identification, the angular integration is performed using the CERES-TRMM BB SW ADMs. Considering the appropriate CERES-TRMM ADM scene type, the instantaneous SW flux, $F_{ani}(\theta_s)$, is computed from the directional SW BB radiance, $L_{sw}(\theta_s, \theta_v, \phi)$, by using:

$$F_{ani}(\theta_s) = \pi \cdot \left( L_{sw}(\theta_s, \theta_v, \phi)/R(\theta_s, \theta_v, \phi) \right)$$

where, $R(\theta_s, \theta_v, \phi)$, is the ADM dependent anisotropic factor for a given scene type and viewing geometry defined by, $\theta_s$ the solar zenith angle, $\theta_v$ the viewing zenith angle and, $\phi$ the relative azimuth angle, respectively. In practice, the Global Land Cover Map produced by the IGBP (Belward et al., 1999) is used to associate one of the six CERES-TRMM classes to each MS-7 pixels (see Figure 1).

![Figure 1: CERES ADMs surface geotypes as seen by Meteosat-7 imager (green = moderate-to-high vegetation cover = DV, khaki = low-to-moderate vegetation cover = BV, orange = dark desert = DD, yellow = bright desert = BD, cyan = ocean = OC, and blue = ice or snow). Red boxes delimit the four selected zones representative of junction areas between two CERES-TRMM ADMs scene types.](image)

3. STUDY AREAS DEFINITION AND SELECTED MS-7 DATA

To locate the sun glint area in the MS-7 field-of-view (FOV), we have considered that ocean footprints located inside a glint angle threshold value of 15° in each MS-7 slot experienced a sun glint contamination in the measured visible MS-7 radiance. Then, we selected the clear oceanic areas defined by a glint angle lower or equal to 15° on the 12:00 UTC time slots during the month of February 2003 (see Figure 2). To investigate the impact of the ADM anisotropy factor on the retrieved instantaneous SW flux at TOA when the MS-7 radiance measurements originate from footprints containing a mixture of CERES-TRMM scene types we have considered four additional zones in the MS-7 FOV (see red boxes in Figure 1). Each of them have been taken as representative of a junction area between two CERES-TRMM scene types, namely between (1) the ocean (OC) and the low-to-mod tree/shrub coverage (bright vegetation or BV), (2) the OC and the dark desert (DD), (3) the bright desert (BD) and DD, and (4) the BV and the mod-to-high tree/shrub coverage (dark vegetation or DV) scene types, respectively. In each zone, we have then analysed all available 12:00 UTC MS-7 time slot during the month of February 2003 in order to determine for each of them the day exhibiting the largest number of clear sky footprints.
4. ADMS ANISOTROPIC CORRECTION FACTORS AND SUN GLINT

Whatever the number of clear sky ocean pixels involved in the radiance-to-flux conversion (Equation 1) SW fluxes time series displayed on right panels in Figure 3 (solid lines) clearly indicate that the CERES-TRMM BB clear ocean SW ADM anisotropic correction factors (see middle panels in Figure 3) do not allow to satisfactorily retrieve clear-sky reflected TOA fluxes when SW radiance values are contaminated by sun glint (see left panels in Figure 3). Indeed, the angular bins used to define the CERES ADMs (namely, a 10° or 20° step from 0° to 180° for the relative azimuth angle - ADMs are assumed to be azimuthally symmetric about the principal plane - and, nine angular bins from 0° to 90° in a 10° step for the solar and viewing zenithal angles, respectively) still appear too coarse to adequately account for the large radiance variations when satellite viewing geometry moves towards the ocean specular reflection direction. To overcome such a difficulty, Loeb et al. (2003) proposed to bypass radiance measurements affected by sun glint and estimate fluxes in cloud-free sun glint by the corresponding ADMs TOA flux (actually the TOA albedo) interpolated at the solar zenith angle of observation:

\[ F_{\text{alb}}(\theta_s) = E_0 \cdot \cos(\theta_s) \cdot A(\theta_s) \]  

where \( E_0 \) is the solar constant corrected for Sun-Earth distance and, \( A(\theta_s) \), the BB SW ADM TOA albedo.

Right panel in Figure 3A indicates that the difference between the \( F_{\text{ani}} \) (solid line) and \( F_{\text{alb}} \) (dashed line) fluxes can reach up to 140 W.m\(^{-2}\) (equivalently to a relative difference of about 150 %) for a given footprint at time of the strongest sun glint contamination. Averaged over all the clear ocean pixels located inside the pre-defined sun glint zone on the 15 February 2003, the difference between the two fluxes at time of the strongest sun glint perturbation reduces to about 27 Wm\(^{-2}\) (equivalently to a relative difference of about 28.5 %) (see the right panel in Figure 3B) and drop to about 7.2 Wm\(^{-2}\) (equivalently to a relative difference of about 7.5 %) when averaged for the entire month of February 2003 (see the right panel in Figure 3C). Note that this reduction in the flux magnitude difference originates in the simple sun glint discrimination method we used to define the sun glint area and the presence of cloudy pixels as pixels located inside the selected sun glint area are differently contaminated by sun glint and the presence of clouds can potentially unable to account for strongly contaminated pixels in the clear sky averaging process.

Besides the flux overestimation at time of sun glint contamination, use of Equation 1 also leads to a flux underestimation prior and after the time of strongest sun glint perturbation as well highlighted when comparing the \( F_{\text{ani}} \) and \( F_{\text{alb}} \) time series in the right panels Figures 3 (solid vs. dashed lines). The difference between the two curves on the right panel in Figure 3A indicates that the retrieved SW fluxes are affected by sun glint during approximately 7 hours while in the other hand the SW radiance time series displayed on the left panel in Figure 3A only reveals a sun glint contamination of about 2 hours. The two periods of SW flux underestimation surrounding the time of strong sun glint perturbation originate in the CERES-TRMM ocean ADM anisotropic factor (see middle panels in Figure 3) which tends to over-correct the SW radiance in the vicinity of the sun glint period when performing the SW radiance-to-flux conversion.
Figure 3: Time evolution (from sunrise to sunset) of the SW radiances (left panels), the CERES-TRMM SW Ocean ADM 5 anisotropic correction factors (middle panels) and, reflected SW fluxes at TOA corresponding first to (A) a single clear sky oceanic footprint located inside the pre-defined sun glint zone in the MS-7 12:00 UTC time slot on 15 February 2003, second to (B) the clear sky area averaged values on 15 February 2003, and finally to (C) the February 2003 monthly mean and area averaged values. In right panels, solid lines account for SW fluxes computed according to Equation 1, dashed lines for SW fluxes computed according to Equation 2, and finally, dotted lines for SW fluxes computed according to Equation 3.
Because CERES-TRMM BB SW ADMs can only deliver climatological flux values, we propose to take advantage of both, the high temporal sampling of the sun glint region afforded by the geostationary orbit of the Meteosat satellites and information contained in the empirical CERES-TRMM ADMs when estimating the reflected SW flux at TOA during the time for which a sun glint perturbation of the ADMs anisotropic factor is reported. The method simply consists in multiplying the ADM flux, $F_{\text{adj}}$, by a correction factor, $X(t)$, allowing to account for the actual radiance measurements:

$$F_{\text{corr}}(\theta_s, t) = F_{\text{adj}}(\theta_s, t) \cdot X(t)$$  \hspace{1cm} (3)

with,

$$X(t) = \left( \frac{F_{\text{ani}}(\theta_s, t_i)/F_{\text{adj}}(\theta_s, t_i)}{F_{\text{ani}}(\theta_s, t_f)/F_{\text{adj}}(\theta_s, t_f)} - 1 \right) \cdot \frac{t - t_i}{t_f - t_i}$$

where, $t_i$ and $t_f$ define the time interval during which the correction is applied. By setting $t_i$ equal to the time of the first local maximum appearing in the $F_{\text{ani}}$ clear sky TOA reflected SW flux time series, and $t_f$ to the third local maximum (the second local maximum being due to the flux overestimation at time of strong sun glint perturbation), we correct both, underestimated as well as overestimated fluxes.

The $F_{\text{corr}}$ dotted lines on right panels Figure 3 illustrates the effect of the correction factor on the retrieved instantaneous SW fluxes at TOA. The benefit of this factor over a simple interpolation of the ADM flux at the solar zenith angle of observations is well apparent if we compare the $F_{\text{corr}}$ curves (dotted lines) with the $F_{\text{adj}}$ curves (dashed lines) on right panels in Figure 3.

5. ADMS ANISOTROPIC CORRECTION FACTORS AND MIXED CLEAR SCENE TYPES

Clear sky footprints located in the zones selected as representative of junction areas between two CERES-TRMM scene types (see boxes in Figure 1) were gathered by discrete bins of 10% in surface types coverage. Analysis of the related bin-averaged CERES-TRMM SW BB ADMs anisotropic factors time series (solid lines on middle panels in Figure 4) indicate that while globally, the footprints acquisition geometry does not vary too much throughout a given zone, some discrete coverage bins do not appear to be homogeneously distributed over the entire zone as some discrepancies occur between the bin-averaged anisotropic factor values and values computed from the clear footprints averaged acquisition angles (dotted lines on middle panels in Figure 4) in each zones (see Table 1). Nevertheless, whatever the variations in the footprints acquisition angles maybe, the ADMs anisotropic factors times series displayed on middle panels in Figure 4 clearly indicate that the largest surface anisotropy variations between clear CERES-TRMM scene types occur along the coastline of continents where difference in ADMs anisotropic factors can reach up to about 50% (relative difference) between the oceanic and vegetated or desert scene types (see Table 1). While of lower magnitude, Figure 4C.2 reveals that the difference in the ADMs anisotropic factors between the 2 desert surfaces can reach up to 16.2%. By contrast, the anisotropic factor difference between the vegetated surfaces reduces to 1.7% (see Figure 4D.2 and Table 1).

<table>
<thead>
<tr>
<th>Mixed surface types</th>
<th>$\theta_s$</th>
<th>$\theta_v$</th>
<th>$\phi$</th>
<th>$\Delta R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC-BV</td>
<td>66.70</td>
<td>61.14</td>
<td>175.21</td>
<td>0.54 (50.09%)</td>
</tr>
<tr>
<td>OC-DD</td>
<td>44.89</td>
<td>49.82</td>
<td>165.26</td>
<td>0.38 (40.80%)</td>
</tr>
<tr>
<td>BD-DD</td>
<td>48.62</td>
<td>55.65</td>
<td>165.54</td>
<td>0.19 (16.16%)</td>
</tr>
<tr>
<td>BV-DV</td>
<td>21.22</td>
<td>16.44</td>
<td>142.59</td>
<td>0.02 (01.72%)</td>
</tr>
</tbody>
</table>

Table 1: Clear sky footprints averaged acquisition angles (solar zenith angle, $\theta_s$, viewing zenith angle, $\theta_v$, and relative azimuth angle, $\phi$, for each selected zones in Figure 1. Also provided are the ADMs anisotropy correction factors, $\Delta R$, differences at the shifting point between ADMs scene types (relative difference given in percent).

Due to the anisotropy differences between the various CERES-TRMM surface types, a radiance-to-flux conversion (Equation 1) leads, when considering as adequate anisotropic correction factor the ADM anisotropic factor corresponding to the dominant scene type over the mixed footprint, to generate a flux discontinuity at the shifting point between the two ADMs scene types. The magnitude of the flux difference depends on the surface anisotropy difference existing between the two ADM scene types in presence as well illustrated on right panels in Figure 4 (solid lines). The largest fluxes discontinuities take place in coastal
zones at the junction between oceanic and continental surface types. By contrast, the shift from the BV ADM to the DV ADM has only a limited impact on the retrieved fluxes at TOA (see solid line in Figure 4D.3).

Figure 4: Bin-averaged clear sky TOA SW radiances (left panels), anisotropic correction factors (middle panels) and, reflected SW fluxes at TOA (right panels) time series computed from all available clear sky footprints in each zones taken as representative of a junction area between (A) the ocean (OC) and bright vegetation (BV), (B) the ocean and dark desert (DD), (C) the bright desert (BD) and the dark desert, and (D) the bright vegetation (BV) and dark vegetation (DV) surface types. In middle and right panels, solid lines account for time series computed according to the highest percent coverage ADM scene type approach, and dashed line for time series computed according to the climatological ADMs fluxes ratios.
To remove such artificial fluxes discontinuities, we will consider the radiance over a mixed surface types footprint as being a linear combination of the responses of each component which is assumed to be in the mixture. Then, considering a mixture of two components, the MS-7 SW radiance can be written:

\[ L^{\text{mix}} = p_1L_1 + p_2L_2 \]

which converted in terms of flux gives:

\[ F^{\text{mix}} = p_1F_1 + p_2F_2 \]

where, \( L_i \) is the BB SW radiance associated to a scene of type \( i \) appearing in \( p_i \) percent in the footprint and, \( F_i \) the corresponding instantaneous SW flux at TOA. Therefore, based on Equation 1, the anisotropic correction factor for the mixed scene, \( R^{\text{mix}} \), can be write as follow:

\[ R^{\text{mix}} = \pi \cdot \frac{(p_1L_1 + p_2L_2)/(p_1F_1 + p_2F_2)}{(p_1R_1 + p_2R_2,F_2/F_1)//(p_1 + p_2,F_2/F_1)} \]  

(4)

where, \( R_1 \) and \( R_2 \) are the CERES-TRMM BB SW ADMs correction factors corresponding to the CERES-TRMM scene of types 1 and 2, respectively.

Approximating the unknown \( F_2/F_1 \) ration by the ratio of the corresponding CERES-TRMM BB SW ADMs climatological SW fluxes at TOA or equivalently by the ADMs TOA albedo ratio, \( A_2/A_1 \), Equation 4 reduces to:

\[ R^{\text{mix}} = \frac{(p_1R_1A_1 + p_2R_2A_2)}{(p_1A_1 + p_2A_2)} \]  

(5)

Dashed lines on middle panels in Figure 4 display for each zones the evolution of the bin-averaged mixed scene types anisotropic correction factors computed according to Equation 5. Clearly, whatever the two CERES-TRMM scene types in presence, the mixed scene types anisotropic factors allow a smoother transition between the two ADMs scene types and the jump we previously reported when shifting from one ADM scene type to another (dashed vs. solid lines on right panel in Figure 4) do not appear any more.

Now, regarding the bin-averaged SW fluxes time series resulting from a radiance-to-flux conversion using the mixed surface types anisotropic correction factors instead of the ADMs anisotropic factors, we can note on right panels in Figure 4 (dashed vs. solid lines) that all the fluxes discontinuities occurring when shifting from one ADM scene type to another have been fully removed whatever the two surface types in presence. However, as the computation of the mixed anisotropic factors rely on the assumption that the unknown ratios between the reflected SW fluxes at TOA over the actual surface types are equivalent to the ratios of the corresponding climatological ADMs fluxes, the score of the method will have a temporal component. Errors in the retrieved SW at TOA will depend on the magnitude of the differences existing between the physical and optical properties of each surface within the footprint and the associated CERES-TRMM scene types and the magnitude of the anisotropy difference between the scene types contained in the footprint. In practice, we can reasonably assume that they will be negligible in regards to the ones introduced without accounting for mixed scene types anisotropic correction factor.

6. CONCLUSIONS

While the recently developed CERES-TRMM BB SW ADMs (Loeb et al., 2003) undoubtedly represent a major advance over previous ADMs regarding the number of available ADM scene types as well as in terms of angular bins resolution, this latter still appears to coarse to adequately account for the large radiance variations when satellite viewing geometry moves towards the ocean specular reflection direction. Moreover, as no attempt was done to derive models for mixed scene types, use of these ADMs do not allow to account for modifications in factors affecting the anisotropy of surface-leaving radiances in case of footprints containing a mixture of scene types which therefore causes systematic errors in the retrieved SW flux at TOA. Taking advantage of the high temporal sampling afforded by the geostationary orbit of the Meteosat-7 satellite and the information enclosed in the CERES-TRMM BB ocean SW ADMs, we have show that it is possible to provide valuable clear sky fluxes estimation from radiance measurement contaminated by sun glint. Moreover, in the absence of available ADMs for mixed-scene types, our results indicate that it is possible to combine the existing CERES-TRMM BB SW ADMs to derive valuable mixed CERES-TRMM scene types anisotropic correction factors.
7. ACKNOWLEDGEMENTS

This study was supported by the “PRODEX Program” (contract PRODEX-7 no.15162/01/NL/Sfe (IC), Belgian State, Prime Minister’s Office, Federal Office for Scientific, Technical and Cultural Affairs).

8. REFERENCES


