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EFFECT OF A SPHERICAL ATMOSPHERE IN THE IRRADIANCE ESTIMATE FROM RADIANCES MEASURED BY SATELLITE-BASED INSTRUMENTS

Seiji Kato* and Noman G. Loeb
Center for Atmospheric Sciences
Hampton University, Hampton, Virginia

1. Introduction

Spherical geometry of the earth is often neglected when we study radiation budget of the atmosphere. When we look at CERES data, however, we do notice effects of the geometry such as non-negligible radiances at viewing zenith angle greater than 90° or at the solar zenith angle greater than 90°. The purpose of this study is to estimate the effect of the spherical geometry of the earth in estimating the irradiance from Cloud and the Earth's Radiant Energy System (CERES, Wielicki et al., 1996) radiance measurements.

Following Loeb et al. (2002), two reference altitudes are defined. These are 1) the viewing zenith angle reference level which defines the altitude at which viewing zenith angles are defined and 2) the irradiance reference level which defines the altitude at which irradiances are defined. For a spherical earth, the viewing zenith angle for a line-of-sight depends on the altitude where it is defined. For example, the viewing zenith angle is smaller than 90° at a higher altitude for a line of sight tangent to the earth's surface (Figure 1). As a consequence, if the viewing zenith angle is defined at the surface, radiances at viewing zenith angles greater than the earth's tangent angle are not included in the irradiance computation. In addition, since irradiance is radiant flux, the irradiance in the radial direction depends on the radius of the sphere, hence, the altitude at which flux is computed. As we can see in the later in this paper, the irradiance changes approximately by 10% going from the irradiance reference level at 350 km to the surface. The two objectives of this study are:

1 To estimate the contribution of radiances from viewing zenith angle greater than the earth's tangent angle in irradiance computations.

2 To define the optimum irradiance reference level for climate studies.

* Corresponding author address: Seiji Kato, Mail Stop 420, NASA Langley Research Center Hampton, VA 23681-2199; e-mail s.kato@larc.nasa.gov.

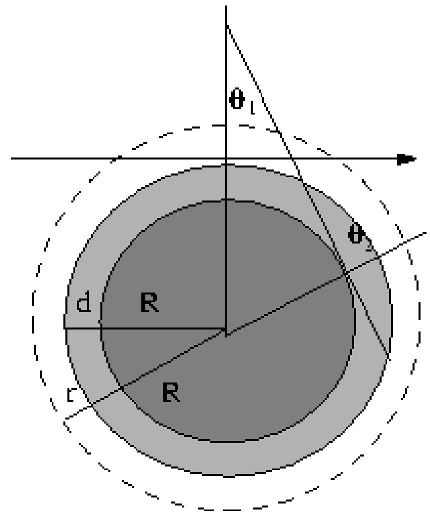

Figure 1 Schematic diagram of a spherical earth. The viewing zenith angle defined at a higher altitude (θ_1) is smaller than the viewing zenith angle of 90° (θ_2) defined at the surface for a line of sight.

2. Viewing Zenith Angle Reference Level

Figure 2 shows the azimuthally averaged radiance measured by the CERES instrument from January 1998 to August 1998 and March 2000 for all sky conditions as a function of viewing zenith angle. The viewing zenith angle is defined at 100 km in the figure. The radiance decreases toward the viewing zenith angle of 90° and is negligibly small at 90°. If the viewing zenith angle is defined at the surface, however, the radiance at 90° (shown by the dotted line) is not negligible. Therefore, if the viewing zenith angle is defined at the surface, the integration from 0 to 90° to compute the irradiance does not include radiances at viewing zenith angle greater than the tangent angle of the earth's surface. As a consequence, when the viewing zenith angle defined at the surface is used for the irradiance computation, the resulting irradiance is approximately $2\mathrm{Wm}^{-2}$ less than the irradiance computed with the viewing zenith reference level of 100 km. This is illustrated on Figure 3. First, the irradiance is computed using the viewing zenith reference level of 350 km, which is the satellite altitude. The solid line in Figure 3 indicates the irradiance that is scaled inversely proportional to square of the distance to the center of the earth by $F(350)[(350+R)/(r+R)]^2$, where R is the radius of the earth and r is the irradiance reference level. The closed circle in Figure 3 shows that the irradiance computed with the viewing zenith reference level indicated by the abscissa. If radiances at the viewing zenith angle greater than 90° defined at a viewing zenith angle reference level is negligible and all radiance contributions are accounted for when integrating radiances from 0° to 90°, then the closed circle lies on the solid line. When the viewing zenith angle is less than 30 km, the irradiance is less than $F(350)[(350+R)/(r+R)]^2$. At the surface, the difference is the contribution of radiances of which the viewing zenith angle is greater than the tangent angle of the earth's surface to the irradiance. Based on this analysis, the viewing zenith angle reference level has to be greater than 30 km.

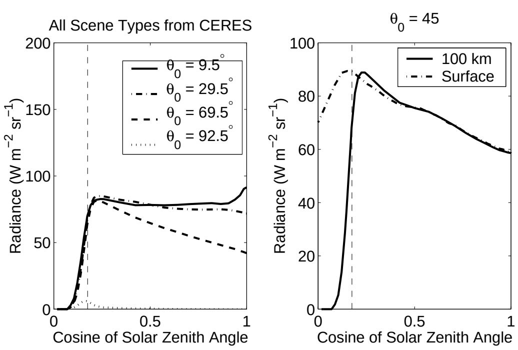

Figure 2 Radiance as a function of cosine of the viewing zenith angle for different solar zenith angles. The radiance is the average value of all-sky 9 months of CERES data. The viewing zenith angle of the CERES instrument is computed at 100 km. The vertical dashed-line indicates the tangent angle to the earth's surface.

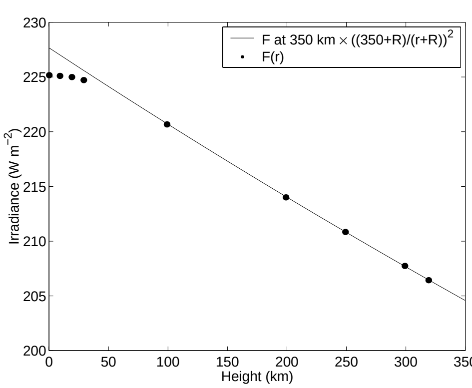

Figure 3 Irradiance computed from CERES data using different viewing zenith angle reference levels (closed circles). The solid line indicates the irradiance computed with the viewing zenith angle reference level at 350 km and scaled inversely proportional to square of the distance to the center of the earth.

In order to check the results obtained from CERES data with theory, we run MODRTAN (Kneizys et al., 1988) using two extreme conditions; one with a molecular atmosphere and the other with a very thick cloud extending from the surface to 15 km. When a molecular atmosphere is used in the computation, the difference between the irradiance for the viewing zenith angle defined at the surface and 100 km is approximately 1 $\mathrm{Wm^{-2}}$. When a cloud extend from the surface to 15 km, the difference is approximately 3 $\mathrm{Wm^{-2}}$. Therefore, the value estimated from CERES data falls between these two extreme values.

Once the irradiance is computed using the viewing zenith angle reference level above 30 km, all radiances contribute to the irradiance are included in the irradiance estimate. Therefore, the irradiance is inversely proportional to square of the distance from the viewing zenith angle reference level to the center of the earth. The value of the irradiance, however, changes by about 10% depending on the irradiance reference level. In the following section, therefore, we determine the optimal irradiance reference level for climate studies.

3. Irradiance Reference Level

Assume that the earth is illuminated by solar radiation with irradiance I_0 (Figure 1). Over an arbitrary time period, the energy is either reflected E_{ref}, absorbed E_{abs} or transmitted E_{trans} by the earth system. Therefore,

$$E_{tot} = E_{ref} + E_{abs} + E_{trans}. \tag{1}$$

In order to avoid treating transmission explicitly in estimating the energy balance of the earth, we need to determine the irradiance reference level d such that

$$E_{tot} = \frac{(R+r)^2}{(R+d)^2}(E_{ref} + E_{abs}), \tag{2}$$

where r is the viewing zenith angle reference level and is greater than 30 km. Since $E_{tot}/\pi(R+r)^2$ is equal to I_0, this is equivalent to adjusting the sum of reflected and absorbed irradiance by reducing d from r. At d, the sum of E_{ref} and E_{abs} equal to E_{tot}. This, therefore, is equivalent to assume a hypothetical atmosphere of height d that is opaque to solar radiation and transparent above d. This hypothetical atmosphere intercepts the same amount of energy as the real atmosphere of the earth.

In order to determine the irradiance reference level d, we obtain spectral dependent extinction by the atmosphere using MODTRAN (Figure 4). We considered two conditions, a molecular atmosphere and an atmosphere with a cirrus cloud at 10 km. For both cases, the irradiance reference level is approximately 20 km.

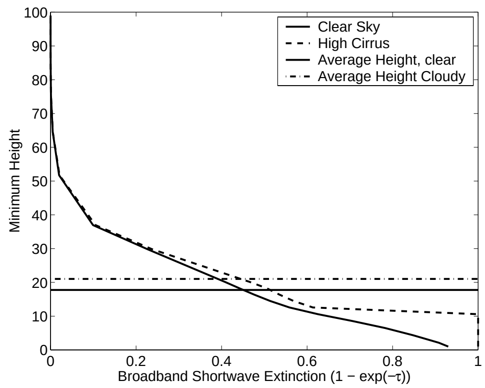

Figure 4 Extinction of the solar irradiance through the earth's atmosphere as a function of the minimum altitude of the path. The path is shown in Figure 1 by a horizontal line with an arrow. The extinction is computed for two types of the atmosphere, a molecular atmosphere (solid line) and the atmosphere with a cloud layer at 10 km (dashed line). Two horizontal lines indicate the height of the atmosphere that intercepts the equivalent energy if the atmosphere is completely opaque below the height and completely transparent above the height.

To summarize, the viewing zenith angle reference level needs to be greater than 30 km in order to include all radiances in irradiance computations. When the irradiance is scaled inversely proportional to square of the distance to the center of the earth and is computed at the surface, it is approximately 2 $\mathrm{Wm^{-2}}$ greater than the irradiance computed with using the viewing zenith reference angle at the surface (Figure 5 solid line). When the irradiance computed with the viewing zenith angle reference level greater than 30 km is scaled to the irradiance reference level of 20 km, the resulting irradiance is approximately 1 $\mathrm{Wm^{-2}}$ greater than the irradiance computed with the viewing zenith angle reference level at the surface (Figure 5 dash-dot line).

4. Conclusions

1. To include all non-negligible radiances in the upward irradiance estimate, the viewing zenith angle reference level needs to be at least 30 km.
2. When the surface is used to determine the zenith angle for the irradiance integration, the resulting irradiance is 1 to 2 $\mathrm{Wm^{-2}}$ less than the irradiance computed with the viewing zenith angle reference level at 100 km.
3. The optimal altitude to compute irradiances (irradiance reference level) for climate purpose is 20 km.

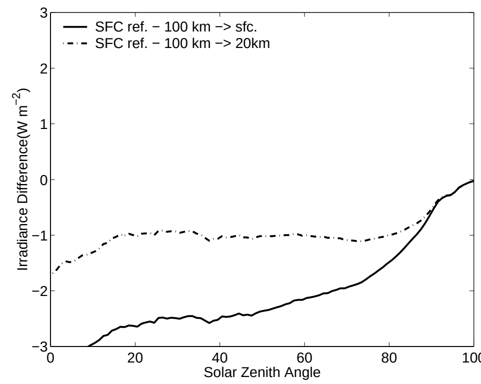

Figure 5 Irradiance difference as a function of solar zenith angle. The difference is computed by subtracting the irradiance computed with the viewing zenith angle reference level at 100 km and scaled inversely proportional to square of the distance to the center of the earth to the surface (solid line) and to 20 km (dash-dot line) from the irradiance computed with the viewing zenith angle reference level at the surface.

Acknowledgments

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