THE WAVELENGTH-DEPENDENT TRANSMITTANCE OF THE CLOUDS IN THE 350-1000 nm RANGE

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Abstract. *Spectral irradiance in the NUV-NIR (350-1000nm) measured at Laboratório de Energia Solar in the Universidade Federal do Rio Grande do Sul was used to determine the spectral attenuation of solar irradiance by an homogeneous cloud-layer. Generally, the literature on cloud transmittance suggests that clouds act as somewhat of a neutral density filter in this region of the spectrum. The transmittance of the cloud-layer was found to be wavelength-dependent in the 350-1000nm range. Therefore the grey hypothesis is not fully applicable for these kind of clouds.*

Keywords: *Solar radiation, Spectral irradiance, Cloud transmittance*

1. INTRODUCTION

The analysis of the spectral radiation flux reaching the earth surface is very important for the study of the energy exchange mechanisms. Solar radiation provides the main input to the energy balance, since the fraction absorbed at the ground surface is transformed to sensible, latent, and subsurface heat fluxes. Clouds, aerosols and atmospheric gases contribute to attenuate the incoming solar radiation through both scattering and absorption processes. In particular, optically dense clouds in the sun path can almost totally extinguish the direct solar irradiance. In such occasions the global solar radiation measured at the ground is due mainly to the diffuse radiation. When there are clouds in the sky but not in front of the Sun, the global solar radiation can often present appreciably higher values than those measured in cloudless days. This is because the clouds can scatter very efficiently the solar radiation towards the ground. Therefore, clouds with large optical depth are expected to cause a significant change on the solar radiation at ground level as well as at higher altitudes, as they reflect back to outer space a considerable part of the incoming solar radiation. Clouds also exert a strong influence on the net radiation balance at the terrestrial surface, since they emit thermal radiation toward the ground and cause, at the same time, scattering and absorption of the long-wave radiation (Kondratyev, 1969).

Thus, it becomes evident that clouds can cause large variability in solar irradiance on the ground. In this paper we will demonstrate that the clouds also play an important role on the spectral distribution of the solar radiation. Therefore it is import to know how the attenuation by clouds depends on the wavelength. A large number of studies assumes that the attenuation by clouds is uniform across the UV, visible and near IR spectrum and use that assumption for the evaluation of the role of clouds in the distributions of the solar radiation. From the point of view of physical optics, clouds are an example of a very opaque medium. Radiation properties of such mediums are determined by the values of scattering and absorption of radiation by separate particles, in this case hydrometeors or ice particles. However first attempts have been made to investigate how the spectral transmission of clouds deviates from an assumed neutral density filter (Nann and Riordan, 1991). In the last decade spectral studies have gained importance. Earlier papers conclued that the scattering of radiation by clouds is essentially wavelength independent (Josefsson and Landelius, 2000). Later papers present mainly wavelength dependent cases. Schwander et al. 2002 and Sabburg and Long 2004 showed that, for cloudy sky, the global irradiance increases with decreasing wavelengths. The present study gives an example for the attenuation by an almost homogenous cumulus cloud present in the sun path not spectrally flat in this wavelength range. For our study we use the term *transmittance of a cloud* for the ratio of direct irradiance with cloud cover to the irradiance without cloud on the sun path.

2. BRIEF THEORETICAL BACKGROUND

The interaction of light with cloud and precipitation particles (i.e., hydrometeors), as can be seen in a variety of spectral optical phenomena, has long intrigued scientific observers and led to fundamental advances in the field of optical physics. The appearance of halo arcs and rainbows, to name but a few impressive celestial occurrences, actually represents concentrations of reflected, refracted, or diffracted solar radiation in the scattering phase functions of atmospheric particles present in clouds of various shapes, sizes, and orientations.

It is useful to establish some definitions of importance to understanding solar radiation scattering in the atmosphere. There are essentially three scattering regimes that apply: (1) Rayleigh scattering, principally for air molecules and very important to λ <1000 nm; (2) the Rayleigh-Mie transition zone for the majority of aerosols and just-formed cloud particles; and (3) the Mie and geometrical optics domains for cloud and precipitation particles (Mishchenko et. al. 2000). It is important to observe that the term Mie or Lorenz-Mie scattering strictly refers to the electromagnetic interaction with homogeneous isotropic spheres, in dealing with arbitrarily shaped particles is adequate refer to the Mie scattering zone or domain only in the context of having a particle size that is on the order of the wavelength of the illuminating light.

It is also useful to mention that hydrometeors can be distinguished from aerosols by their generally larger size and water/ice-dominated composition. More effectively, they differ by their growth activity, that is, whether they are actively growing/evaporating or (for dry or deliquesced particles) in equilibrium with their environment. Data about aerosols optical depth also is obtained using the spectroradiometer when the sun disc is not obscured by clouds. The rapid transition from aerosol to hydrometeor commonly occurs in the cloud base region as hygroscopic particles swell in updrafts until further growth above vapor saturation is reached (Mishchenko et. al. 2000). Thus, initial hydrometeors scatter light in the Rayleigh-Mie transition zone. The continued growth of the hydrometeors causes them to dominate the quiescent geometrical optics, where scattering is related to the cross-sectional area.

Observations based on spectroradiometers, microwave radar, LIDAR, aircraft optical probes, etc. show that clouds can be formed by water drops (cumulus) with a large variation in size and concentration. Other types of clouds, as elevated thin cirrus, are largely composed of bullet rosettes, solid and hollow columns, plates, aggregates, and ice crystals with irregular surfaces with sizes ranging from a few micrometers to 1000 μm (Baran, 2004). These idealised geometries that are used to represent real ice crystals are shown in Fig. 1.

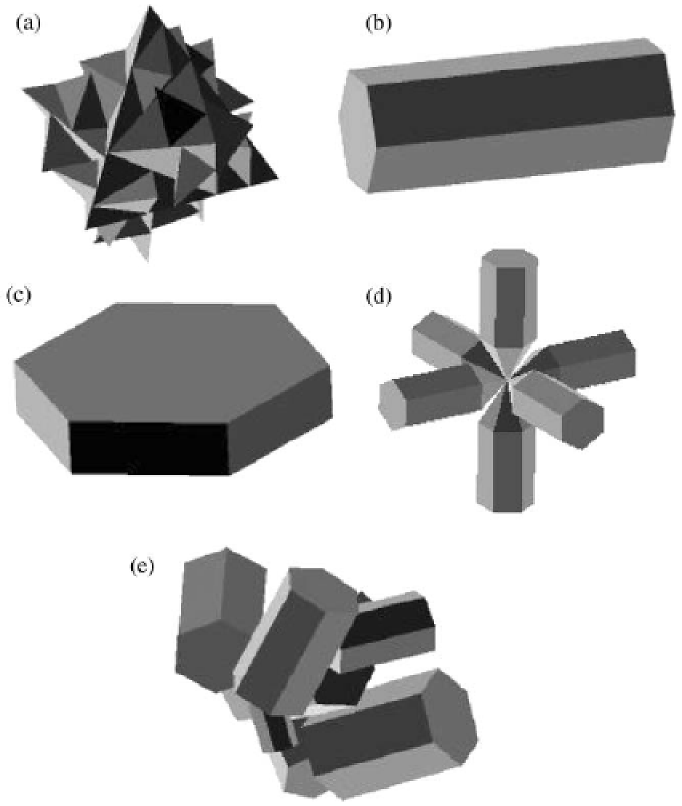

Figure 1. Mathematical idealisations of various ice crystal geometries showing (a) randomised polycrystal, (b) hexagonal ice column, (c) hexagonal ice plate, (d) 6-branched bullet rosette and (e) randomised hexagonal ice aggregate. Adapted from Baran (2004).

In addition to the nonspherical shape problem, a large variation of size parameters also presents a basic difficulty in light-scattering calculations at the UV, visible and infrared wavelengths. The scattering of light by "ideal spheres" can be solved by the exact Mie theory and computations can be performed for the size parameters that are practical for atmospheric radiation applications. However, an exact solution for the light scattering in non "ideal spheres" or nonspherical ice crystals covering all sizes and shapes that occur in Earth atmosphere does not exist in practical terms. A mathematical solution with embedded theoretical background for the interation between solar radiation and clouds is beyond the scope of this paper and can be found in Liou, K., (1976) and Mishchenko et. al. (2000).

3. OBSERVATIONS

Spectral-irradiance data collected with a StellarNet EPP2000 spectroradiometer at the Solar Energy Laboratory of the Universidade Federal of Rio Grande do Sul (Porto Alegre, RS, Brazil) on 22 January 2009 were analyzed. In that particular day the sky presented low-altitude, non-precipitating cumulus clouds. Near noon only an isolated cumulus cloud was visible. Measurements were taken at 14h36m UT, when this cloud covered the sun disc. The direct solar irradiance under the referred conditions was then simulated with the SMARTS2 radiative transfer code (Gueymard, 1995). Radiosonde soundings data provided atmospheric profiles of pressure, temperature, and water vapor. Total column amounts of water vapor also was available from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor aboard the TERRA and AQUA satellites. Data from MODIS sensor also provided ozone column amount.

The StellarNet EPP2000 spectroradiometer has the following characteristics: holographic grating monochromator with 600 lines/mm, a useful wavelength range of 350 to 1000 nm, a bandwidth of 4 nm, a user-selectable scan step size and a total scan time of 0.1 s. This spectroradiometer was modified by adding a Teflon diffuser, which improve the cosine/azimuth response of the instruments for measuring global irradiance and a collimator tube with a 5 ° field of view and which are used for measuring direct-normal spectral irradiance. The spectroradiometer is shown in the Fig. 2.

Figure 2. Spectroradiometer EPP2000 and portable computer to measure the spectral cloud transmittance in the Laboratório de Energia Solar of UFRGS (lat. 30.1S, long. 51.1W).

4. RESULTS

The spectral cloud transmittance was determined using as reference the value of direct irradiance measured just before (few seconds) the transit of the cumulus cloud in front of the Sun, ensuring clear-sky references reasonably close, in space and time, to each of the cloudy spectra. This methodology is shown in Fig. 3.

In Fig. 4 is shown the direct beam normal irradiance for different cloud transmittances during the transit of the cloud

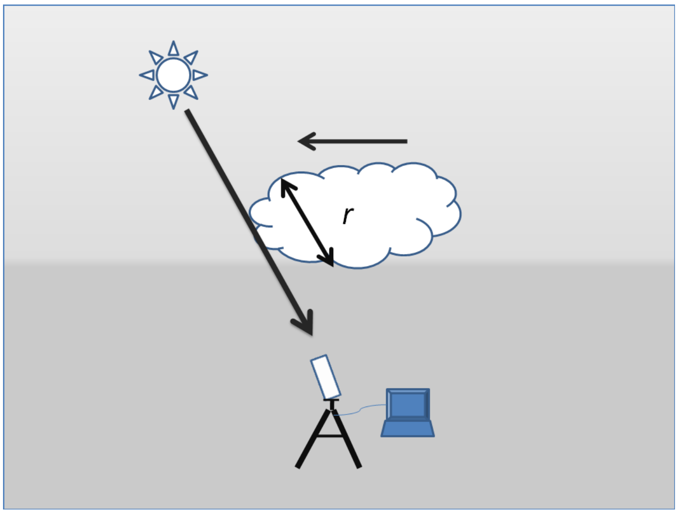

Figure 3. Metodology used to estimate spectral transmittance for different cloud optical depth.

in front the sun disc. For clarity only 8 spectra are shown. All these measurements were taken in less than a minute period. In this period the other variables (precipitable water column, aerosol optical depth, solar position and others) are assumed to be constant. Thus the variability of direct normal irradiance is function only of the extinction caused by the cloud.

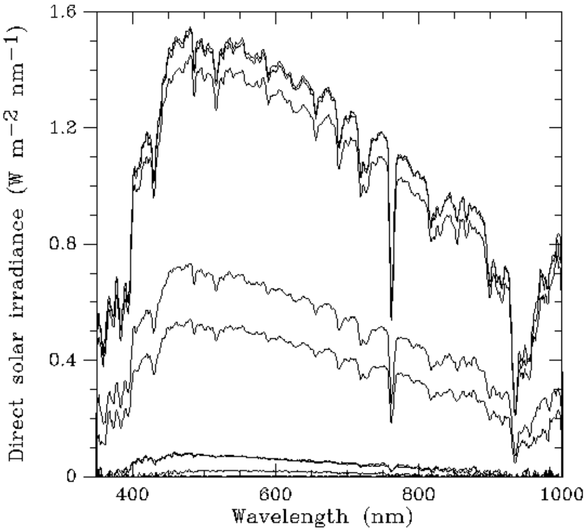

Figure 4. Measured beam normal irradiances, 22 January 2009 at 14h36m UT.

Different transmittances of were measured with the spectroradiometer while the cloud was crossing the sun path, corresponding to distinct cloud thickness (r). The transmittance, T, of an isolated cloud can be defined by (1) as:

$$T = \frac{downward\ flux\ below\ cloud}{downward\ flux\ at\ top\ of\ cloud} \tag{1}$$

The transmitance varies from unity (when the cloud just approaches the sun disc) to near zero (when the cloud become optically thick and almost no direct irradiance is received by spectroradiometer). In the exponential regime, the spectral transmittance also can be related to the cloud thickness and flux extinction coefficient k_{ext}:

$$T_{\lambda,r} = \exp\left[-r * k_{ext}(\lambda)\right] \tag{2}$$

Figure 5 shows plots for six normalized spectral transmittances for different cloud thicknesses. The variation of k_{ext} with wavelength is apparent in Fig. 5. Figure 5a shows a weak absorption of direct beam and represents the initial moment when the cloud begins to cross the sun disc. A moderate absorption is visible in Fig. 5b, c, and d. The transmittances in Fig. 5e and f show a strong direct beam attenuation. The absorption by water vapor near 940 nm also is visible in the Fig. 5. On the other hand, the transmittance near UV is significantly affected by scattering. Figure 6 shows the global irradiance for two cloud optical depths. These measurements were taken almost simultaneously together with the direct solar irradiance.

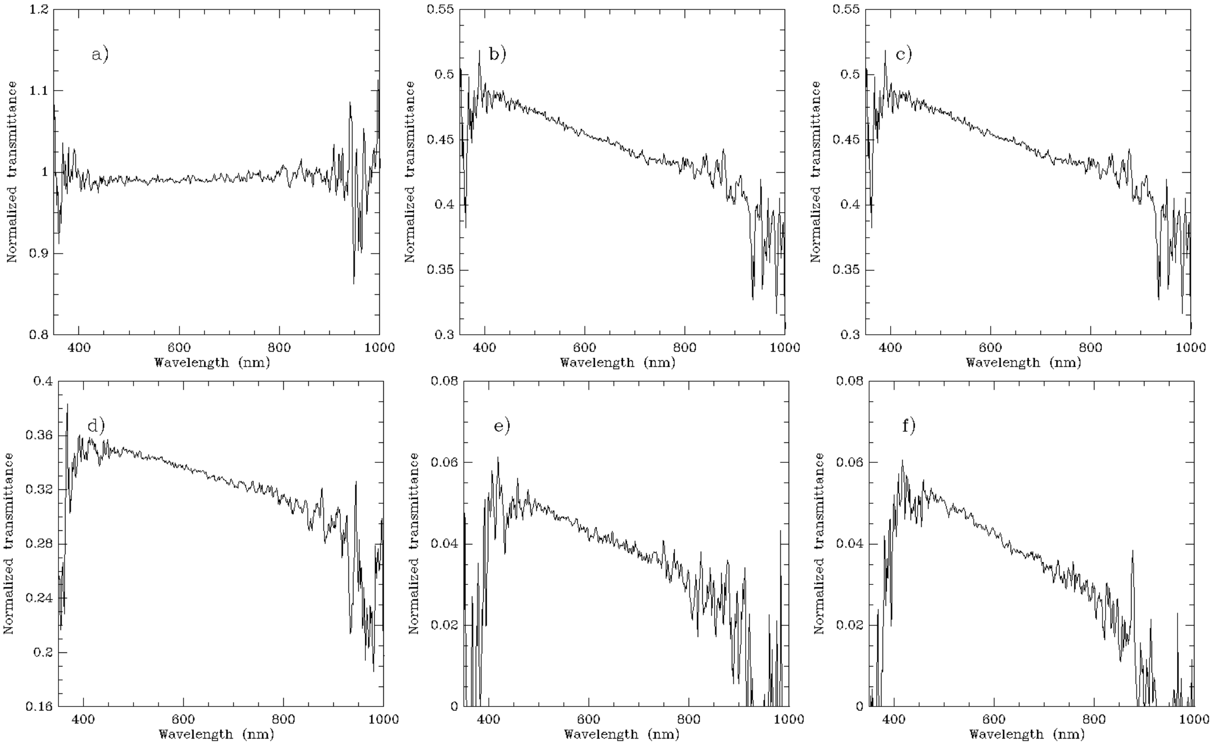

Figure 5. Normalized spectral transmittances for distinct clouds optical depth.

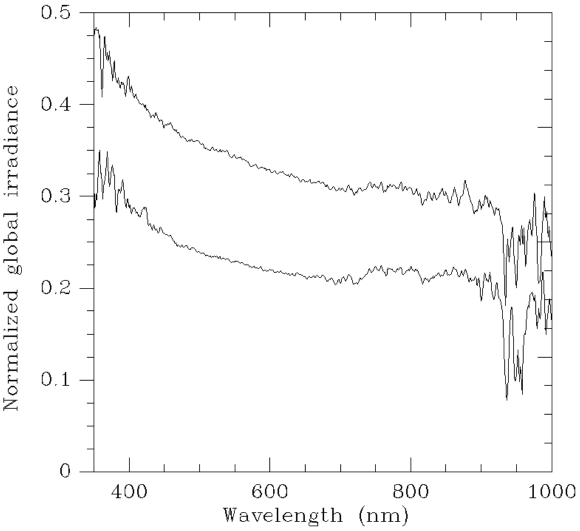

Figure 6. Normalized global irradiance for two different clouds optical depth.

As it can be observed in Fig. 6, the global horizontal irradiance also presents a nonuniform spectral distribution when the sun disc is obscured by the cumulus cloud. A strong absorption in the water vapor band also is noticeable in the global irradiance. Differently to the direct irradiance, an increase of irradiance in the near UV range can be observed. This result was expected due to the diffuse nature of the radiation in the ultraviolet wavelengths. Ultraviolet radiation is scattered much more efficiently by atmospheric aerosols and air molecules compared to the whole shortwave spectrum.

5. CONCLUSIONS

In this work we present measurements of the spectral transmittance of solar fluxes by a cumulus cloud. The present study gives an example of the attenuation on the solar irradiance caused by cloud covering. The obtained spectral transmittance is nonuniform in the 350-1000 nm range and the cumulus clouds show a significant wavelength dependence. Despite no physical considerations were addressed in this paper, an explanation is that the spectral effects induced by cumulus clouds are because the radiation is reflect and then scatters downward again by Rayleigh scattering. Because of the increase of the optical depth, due to the air molecules, with the decrease of the wavelength these photons have a higher chance to be scattered downward again. This is an initial attempt to determine correlations of spectral distribution of solar radiation with both cloud amount and cloud type. These correlations provided useful information for the determination of cloud parameters and for understanding the absorption, scattering and emission processes of solar radiation caused by clouds.

6. ACKNOWLEDGEMENTS

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