CORRESPONDENCE

Comments on "The Ratio of Diffuse to Direct Solar Irradiance (Perpendicular to the Sun's Rays) with Clear Skies—A Conserved Quantity Throughout the Day"

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1. Introduction

In their analysis of diffuse and direct solar irradiances, Peterson and Dirmhirn (1981, herein referred to as PD) conclude that the ratio of diffuse to direct irradiance remains constant through the course of a cloudless day. They state that: "Only in areas of heavy air pollution does diffuse irradiance follow a daily trend." While we find no fault with their scenario for a heavily polluted urban area, we feel that it is perhaps an oversimplification of the general effect of pollution on the diffuse/direct ratio. In addition, we question whether the results of PD have the general widespread temporal and spatial applicability that the authors imply. The purpose of this comment is to present results of theoretical and experimental work that show that instead of being a conserved quantity, the ratio of diffuse to direct solar irradiance for a cloudless sky is dependent on atmospheric turbidity and solar zenith angle.

The basic nature of both the direct and diffuse components of solar radiation is that they are complex functions of wavelength, aerosol burden and solar zenith angle. For a cloudless sky, the direct component is attenuated by molecular and aerosol absorption and scattering. The amount of attenuation depends on the wavelength of the incident radiation, molecular and aerosol optical depths, solar zenith angle and elevation.

Molecular absorption and scattering of radiation in the ultraviolet to near-infrared wavelengths is accounted for in a straightforward manner by single-scattering theory. However, as the aerosol burden increases, multiple scattering predominates and the major portion of the diffuse radiation is scattered in the forward direction. This process decreases the intensity of the direct beam while significantly increasing the amount of circumsolar radiation. The amount and angular pattern of scattering due to aerosol particles depends on their size distribution and its variation with height, as well as on the ratio of the amount of absorption to the amount of scattering for individual particles (Paltridge and Platt, 1976). Even if information on such aerosol characteristics were available and parameterized for the wavelength interval over which standard solar irradiance measurements are made, there is still uncertainty in specifying the distribution of diffuse radiance throughout the celestial dome. This radiance distribution is strongly dependent on the solar zenith angle, as indicated by the results of Steven (1977) and McArthur and Hay (1981). In short, it is not intuitively obvious that the ratio of diffuse irradiance on a horizontal surface to direct normal irradiance should be a conserved quantity for a cloudless day.

In spite of the complexity of the situation, however, several simple broadband models for clear sky insolation have been developed in recent years. Bird and Hulstrom (1981) compared six of these models, including the Bird model developed by them, and found results from it to agree within 3% of the results from rigorous codes for spectral irradiance in multilayered atmospheric models. Based on their results, it was possible to calculate the theoretical ratio of diffuse to direct irradiance for various zenith angles. The results are shown in Fig. 1 for several combinations of input parameters to the Bird model.

The curves labeled USS are for a U.S. Standard model atmosphere with optical depths for water vapor and ozone of 1.42 and 0.34 cm, respectively. It uses an aerosol model described by Bird and Hulstrom as a rural continental aerosol which produces a moderately clear atmosphere with an aerosol optical depth of 0.27 at 0.5 μm. Data were also available for a midlatitude summer (MLS) atmosphere with the same aerosol model, but with water vapor and ozone optical depths of 2.93 and 0.31 cm, respectively. Results for the diffuse/direct ratio did not differ significantly from those for the USS model, and are not shown. The DAVE curves are for a model atmosphere that has the same amounts of water vapor and ozone as the MLS model, but uses the Haze

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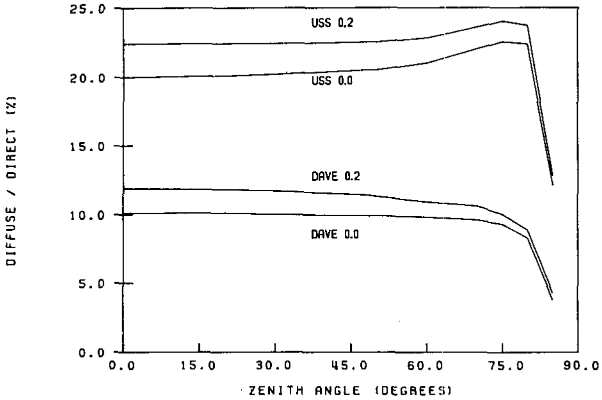

FIG. 1. Bird model ratio of diffuse irradiance on a horizontal surface to direct normal irradiance as a function of solar zenith angle. Curves shown for USS aerosol (0.5 μm aerosol optical depth 0.27) and for Dave aerosol (0.5 μm aerosol optical depth 0.10), and for ground albedo of 0.0 and 0.2.

L (Dave, 1978) aerosol model, which differs considerably from the rural continental aerosol model. The 0.5 μm aerosol optical depth of 0.10 is an indication of the extremely clear nature of this model atmosphere.

The curves of Fig. 1, then, show theoretical effects of surface albedo, aerosol differences and solar zenith angle on the diffuse/direct ratio. For a given aerosol model, an increase in albedo from 0.0 to 0.2 increases the value of the diffuse/direct ratio by 10–15% over a broad range of zenith angles. Differences between the USS curves and the DAVE curves show the effects of the different aerosol models. Most notable of these differences are the lower values of diffuse/direct for the clearer DAVE atmosphere. More subtle differences in the curves for zenith angles between 50 and 80° may be caused by differences in aerosol size and height distributions. Perhaps the most significant feature shown, however, is that for a given aerosol and albedo, the diffuse/direct ratio is constant *only for zenith angles less than ~70°*. For zenith angles greater than 70° the model results show a strong zenith dependence, with the diffuse/direct ratio dropping rapidly with increasing zenith angle.

One of the advantages of using a simple broadband model to express the theoretical behavior of direct and diffuse irradiances is that by its very nature, such a model includes an implicit integration of the diffuse component over the celestial dome and of both components over wavelength. The instrumentation commonly used to measure these components also performs the same implicit integrations. Thus, the ratio of *measured* diffuse to *measured* direct should behave in a manner similar to the model results. It should be noted, however, that most measurements of the direct component include a certain amount of circumsolar (diffuse) irradiance, and measurements of the diffuse component (whether by occulting disk or shadow band) correspondingly exclude some portion of it. The model results, on the other hand, are for the strict definitions of these components. Thus, the only *a priori* differences that one would expect between model results and measurements, resulting from the nature of the measurements, are that measured values of the ratio of diffuse to direct will be smaller than the values computed by the Bird model, for similar conditions.

2. Measurements

Solar irradiance data are recorded as one-minute averages in Ann Arbor at the University of Michigan (42.3°N, 83.7°W, elevation 270 m) as part of the Solar Energy Meteorological Research and Training Site program. Direct normal irradiance is measured with an Eppley normal incidence pyrheliometer (NIP), and diffuse irradiance on a horizontal surface is measured with an Eppley precision spectral pyranometer and continuous-tracking occulting disk. The field-of-view accepted by the NIP and blocked by the disk is 5.7°.

The ratio of measured diffuse to measured direct irradiance has been calculated and plotted for each of 40 cloudless or nearly cloudless days that have occurred here since August, 1979. Results for three representative days are shown in Figs. 2, 3 and 4. Also shown are 0.5 μm aerosol optical depths measured with a Volz sunphotometer.

The data for 17 August 1981 (Fig. 2) are representative of very clear (low turbidity) summer conditions that often occur following the passage of a cold front. Except for a few spikes in the morning due to a few small widely scattered cumuliform

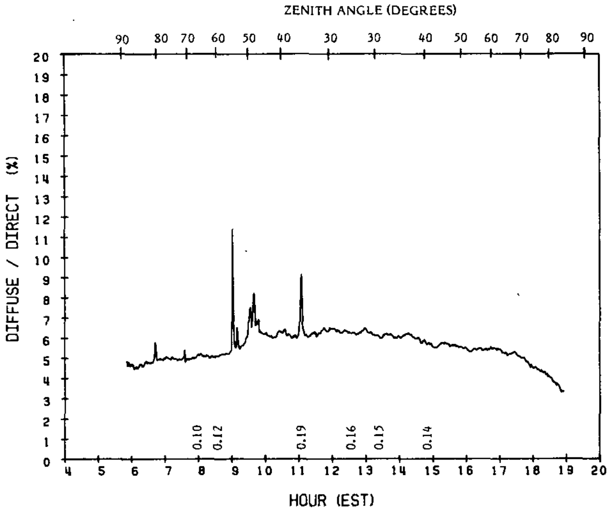

FIG. 2. Measured minute-by-minute ratio of diffuse irradiance on a horizontal surface to direct normal irradiance, Ann Arbor, Michigan, 17 August 1981. Aerosol optical depths at 0.5 μm shown along the abscissa at the approximate times of measurement.

clouds, the diffuse/direct ratio is fairly steady through the course of the day, in agreement with the results of PD. The small diurnal variability of the ratio, with a peak near solar noon, is common on low turbidity days and is apparently related to a small diurnal variation in turbidity. Peterson *et al.* (1981) report observations of a similar diurnal turbidity cycle at rural locations in North Carolina.

The data for 18 August 1981 (Fig. 3) show a continuation of the low turbidity conditions from the previous day, until ~1100 EST. Thereafter, turbidity increased and the diffuse/direct ratio more than doubled its earlier value. The larger values and greater variability of the ratio in the afternoon are typical of clear but turbid conditions here. While the increases shown were associated with a gradual shift in wind direction from a northerly to an easterly direction which caused the measurement site to be downwind of the Detroit metropolitan area, such major urban effects due to this source are seen here only infrequently. Instead, moderate to high turbidities are usually associated with air trajectories from a southerly direction, which may involve long-range transport of pollutants from some of the most industrialized regions in the Midwest.

The data for 30 January 1981 (Fig. 4) are representative of low turbidity winter conditions. A distinct diurnal cycle, such as the one shown here, is a feature common to the data for all cloudless days observed here in late fall and winter. We attribute this diurnal cycle to the fact that the solar zenith angle is large throughout the day for several weeks either side of the winter solstice. For the example shown here, the zenith angle was greater than 60° for the entire day. These results are confirmation of the expectation shown graphically in Fig. 1, that the diffuse/direct ratio is a strong function of zenith angle for large zenith angles.

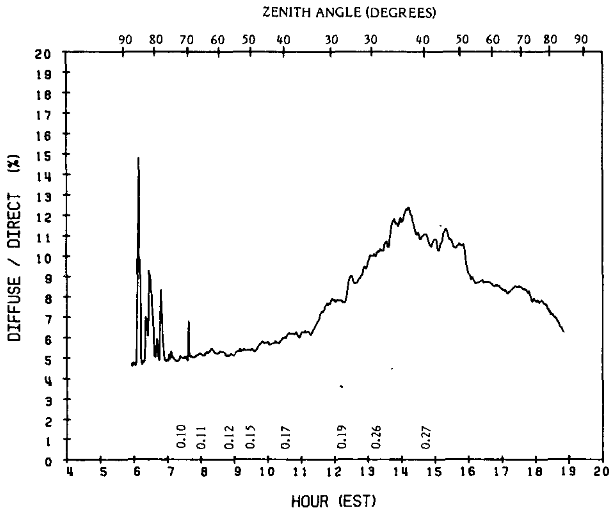

FIG. 3. As in Fig. 2, except for 18 August 1981.

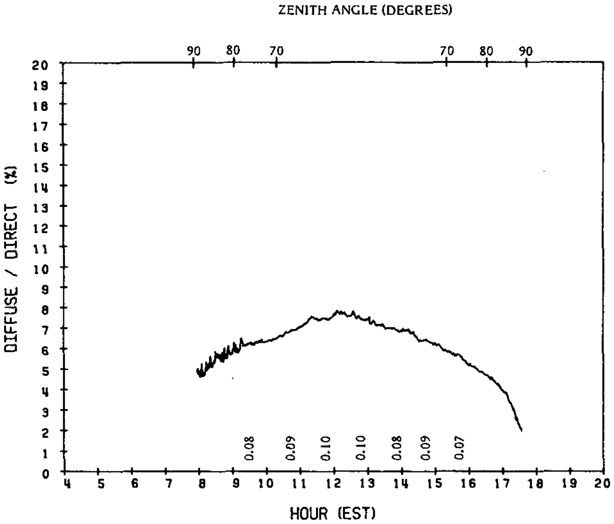

FIG. 4. As in Fig. 2, except for 30 January 1981.

These results, then, indicate that by ignoring turbidity and zenith angle effects on the diffuse/direct ratio, significant errors may be made in estimation of the total diffuse irradiance for a given day from a "single measurement of diffuse irradiance taken at any time of the day" (PD). Such errors may be on the order of 20% for low sun and low turbidity conditions, and as much as 50% for moderate to high turbidities.

3. Conclusions

PD suggest that in rural areas free of heavy pollution, the ratio of diffuse irradiance on a horizontal surface to direct normal irradiance is a constant through the course of a clear day. Our results indicate that changes in turbidity due to changes in the quantity of atmospheric pollutants, be they urban or rural, light or heavy, local or regional, man-made or natural, have a significant effect on the ratio of diffuse to direct irradiance. In addition, both theory and measurements show that the value of the ratio is a strong function of solar zenith angle for large values of that angle. Thus, we feel that general applicability of their results is limited to zenith angles less than ~70°, and to remote and/or high elevation locations where there is a consistently low aerosol burden.

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