A Simple Formula for Determining Globally Clear Skies

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Introduction

Surface measurements to serve as "ground truth" are of primary importance in the development of retrieval algorithms using satellite measurements to predict surface irradiance. The most basic algorithms of this type deal with clear sky (i.e., cloudless) top-to-surface shortwave (SW) transfer, serving as a necessary prerequisite towards treating both clear and cloudy conditions (Cess et al. 1991). Recently, Cess et al. (1995) have used a ratio of surface and top of atmosphere SW cloud forcing to infer the possibility of excess atmospheric absorption (compared with model results) in cloudy atmospheres. The surface component of this ratio relies on inferring the expected clear sky SW irradiance to determine the effects of clouds on the SW energy budget. Solar renewable energy applications make use of clear and cloud fraction climatologies to assess solar radiation resources. All of the above depend to some extent on the identification of globally clear sky conditions and the attendant measurements of downwelling SW irradiance.

Traditionally, cloud fraction information has been provided by surface observer reports and thus is subjective and not continuous. Use has also been made of the downwelling SW record, depending on the magnitude and "smoothness" of the plotted data to estimate clear skies. Because broken cloud and thin cloud effects can equal or actually exceed clear sky downwelling SW irradiance, total downwelling irradiance measurements alone should not be used to determine clear sky.

Other methods used to infer periods of globally clear skies include narrow field-of-view measurements made by instruments such as lidars, ceiliometers, and sun photometers. A time series of this data showing no clouds in the field of view is assumed to represent a lack of clouds in the hemisphere, a problematic assumption in many cases. Recently, digital whole-sky imaging systems have been developed that can produce cloud fraction data, though these systems have difficulty in detecting thin cloud layers. In addition, these systems (like lidars and sun photometers) can be expensive to build and operate, requiring on-site personnel and significant data processing to extract the cloud fraction information. Thus, these types of instruments cannot economically be used in remote areas.

Pyranometers, on the other hand, are relatively inexpensive and robust. The diffuse irradiance can be measured by shading a pyranometer from the direct solar irradiance. The ratio of the diffuse irradiance to the total downwelling SW irradiance is a minimum under clear sky conditions. An empirical fit of the expected diffuse ratio for clear skies for the atmospheric conditions at a given time can be compared with the measured diffuse ratio, thus providing a means to detect periods of globally clear skies. Long and Ackerman (1995) have shown that, for mid-latitude frontal regimes at least, there is a high correlation of pyranometer measurements up to a radius of 90 km. This suggests that identifying periods of clear sky conditions using the global diffuse ratio method can provide an exceptional basis for ground truth comparisons in SW satellite retrieval algorithm development. The diffuse ratio method provides a relatively simple means of identifying globally clear sky conditions in long term data sets such as those archived by the National Renewable Energy Laboratory for the Solar Radiation Research Laboratory in Golden, Colorado, and the Historically Black Colleges and Universities Solar Measurements Network. In addition, methods of using the diffuse ratio to estimate cloud fraction are currently under development. Data sets such as the above can then be processed to retrieve cloud fraction climatologies for solar renewable energy applications.

The Diffuse Ratio

The direct component of solar irradiance is defined as that part of the downwelling SW irradiance reaching the surface which has not been affected by scattering or absorption within the atmosphere. The diffuse component originates from SW radiation that is scattered from the direct solar beam. The total downwelling SW irradiance at the surface is then the sum of the diffuse and the direct components. We define the diffuse ratio as

$$\text{Diffuse ratio} = (\text{diffuse})/(\text{diffuse} + \text{direct}) \tag{1}$$

This ratio has a value ranging from zero to unity.

A base state for the diffuse ratio value at the surface can be defined as that ratio produced from scattering by the homogeneously mixed gases of the atmosphere and absorption by oxygen, ozone, and CO_2 molecules at a given solar zenith angle. We define clear skies to be those which are cloudless. The clear sky diffuse ratio includes the base state, but also becomes a function of the variable aspects of the atmosphere, which are aerosol and water vapor content, and the underlying surface that affect absorption and scattering of SW radiation. To illustrate this dependence, Blunthaler and Ambach (1994) show both a decrease in the direct component and an increase in the diffuse component with increased aerosol optical depth from the Mount Pinatubo eruption. These changes result in an increase in the diffuse ratio from the base state.

The Department of Energy's Atmospheric Radiation Measurement (ARM) Program operates the Southern Great Plains (SGP) Cloud and Radiation Testbed Site located in Lamont, Oklahoma. The ARM Program also conducted a Pilot Radiation Observation Experiment (PROBE) in conjunction with the Tropical Ocean Global Atmosphere/ Coupled Ocean Atmosphere Response Experiment (TOGA/COARE) from November 1992 through February 1993 at a site near Kavieng, Papua New Guinea. Available data from these sites indude measurements of downwelling SW and diffuse SW irradiance, column water vapor amounts, and (in the case of the SGP site) Whole Sky Imager (WSI) images. Because of the propensity for cloudy conditions experienced during PROBE and lack of verification by WSI images, downwelling clear sky SW irradiances were calculated using a delta two-stream model. Profiles of temperature, pressure, and water vapor from sondes serve as the basic input for the computations, along with climatological ozone profiles and an aerosol size distribution determined using sun photometer measurements. Comparisons between model output and measured values of downwelling SW for clear skies give a standard deviation of less than 15 Wm^{-2}. The model total and diffuse downwelling SW irradiance were used in the development of the diffuse ratio method and sensitivity studies. For the SGP site, WSI images from the April 1994 intensive observation period were used to determine periods of globally clear skies for comparison with measurements of total and diffuse SW irradiance. Coincident column water vapor amounts were used for model calculations. This site provided a range of column water vapor amounts from roughly 0.5 to 1.5 precipitable cm, while the PROBE water vapor amounts ranged from roughly 3.5 to 6.5 cm.

The observations and model results have been used to derive an empirical fit to estimate the diffuse ratio for clear sky conditions. This fit includes the cosine of the solar zenith angle and column water vapor amount as independent variables in an equation of the form:

$$DR = C_1 + C_2 *(Wvp) + C_3 *\exp[(C*(CosZ) + C_5*(Wvp)] \qquad (2)$$

where C_n are constants, DR is the clear sky diffuse ratio, Wvp is the column water vapor amount in cm, and CosZ is the cosine of the solar zenith angle. This fitted equation has been tested with encouraging results as shown in the poster presentation given for the ARM Science Team Meeting. However, model sensitivity studies show the need for further development of the method, particularly in the areas of surface albedo and aerosol effects. The cosine of the solar zenith angle is the dominant factor in the clear sky diffuse ratio magnitude and indications are that the method can only be considered useful for zenith angles less than 80°. The sensitivity of the ratio to surface albedo is such that an albedo change of 10% affects the ratio about as much as a change in column water vapor amount of 1 cm. However, with the exception of snowfall, changes in surface albedo generally occur at a much slower rate than column water vapor changes. Thus once the sensitivity to albedo is incorporated it is expected that seasonal values can be used. The effects of aerosol on the ratio have yet to be investigated, primarily due to lack of aerosol optical depth data.

Further Research

With the continuing operation and improvement in data dissemination at the SGP site and the planned installation and long-term operation of an ARM site at Manus, Papua New Guinea, we propose to continue refinement of the diffuse ratio technique for identifying globally clear skies. The Manus site is particularly important in this refinement due to the need for actual clear sky data for high column water vapor amounts to preclude the necessity of using model output. Using upwelling SW measurements available from both sites will aid in the investigation of the seasonal albedo dependence of the ratio. We also propose to use sun photometer or rotating shadow band radiometer data to investigate the effects of aerosols on the method.

A rotating arm mechanism to be used in conjunction with a standard pyranometer is currently under development and testing. This will allow the measurement of both the total and diffuse irradiance by a single instrument, thus removing instrument calibration offset errors in the ratio. This arrangement is envisioned as making possible inexpensive deployment at many sites.

Finally, we propose to use WSI cloud fraction information and time series of both measured and clear sky diffuse ratio data to develop a method of estimating cloud fraction. Along with the deployment of the rotating arm instrument, this will facilitate the retrieval of clear/cloud fraction climatologies from existing and future data sets.

References

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