Detection of Clear Skies Using Total and Diffuse Shortwave Irradiance: Calculations of Shortwave Cloud Forcing and Clear Sky Diffuse Ratio

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The effect of clouds on the shortwave (SW) irradiance near the surface is of interest for surface radiative energy budget studies (Long et al. 1994) and investigation of the recently suggested excess SW cloud absorption (Cess et al. 1995; Ramanathan et al. 1995; Pilewski and Valero 1995). One measure of the effect of clouds is cloud forcing: the difference between clear (i.e., cloudless) sky irradiance and measured irradiance. One way of estimating the surface clear sky irradiance is to calculate it using radiative transfer models, which require aerosol, temperature, pressure, and humidity profiles as input, as well as surface albedo. This information is not readily available in many locations where cloud forcing estimates are desirable.

Clear sky irradiance can also be estimated by empirical fit to clear sky irradiance measurements (for examples of this method, see Waliser et al. 1995 or Cess et al. 1995), which requires the identification of periods of hemispherically cloudless conditions at the instrument site. This identification can be difficult, however, because of the temporal and spatial mismatch between satellite and ground-based observations and the narrow field of view of other ground instruments such as ceilometers, lidars, and cloud radars.

A method has been developed that uses only measurements of downwelling broadband total and diffuse SW irradiance to detect periods of hemispherically clear skies. This detection method uses the known characteristics of typical clear sky irradiance time series. Given the identification of periods of hemispherically clear skies, an empirical fitting algorithm is applied that uses a minimum absolute deviation fitting technique to estimate both the clear sky total SW irradiance and the ratio of diffuse to total SW irradiance (diffuse ratio) as a function of solar zenith angle. The clear sky irradiance and diffuse ratio are then used to determine the clear sky direct and diffuse SW components, and the downwelling SW cloud forcing at the surface. Examples of the empirical fits and estimates of correlation and standard deviations from perfect agreement are presented in the following sections.

Clear Sky Identification

Baseline Surface Radiation Network (BSRN) data from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) central facility taken during the April 1994 intensive observation period (IOP) have been processed to detect periods of clear skies. These results have been compared to Whole Sky Imager (WSI) cloud fraction retrievals and images, given at 10-minute intervals, to verify the algorithm. Figure 1 shows the series of WSI cloud fraction for the periods identified as clear by the method.

The cases with the most disagreement during April 1994 occur on the 15th and 18th. The maximum WSI cloud fraction for these periods is 2.5% at 2040 GMT on the 15th and 11% at 1420 GMT on the 18th. The WSI cloud fraction retrieval appears in error on the 15th when there is an enlarged circumsolar disc, normally due to hazy conditions, and no apparent clouds in the images. This circumsolar disk would not be classified as cloud by an observer, and has little effect on the total SW measured at the surface. For the 18th, the WSI images again show a circumsolar disc, and small

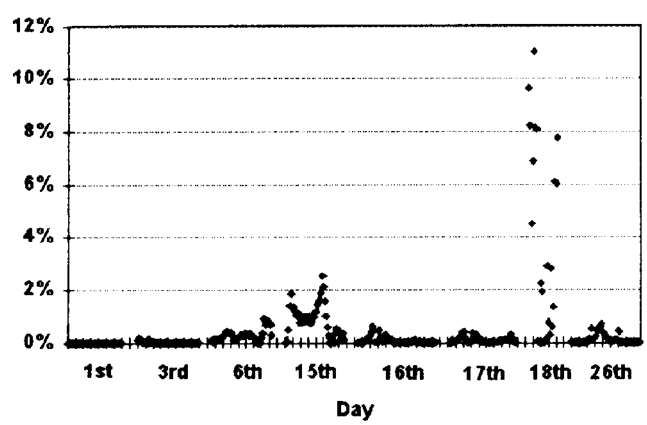


Figure 1. WSI cloud fraction for algorithm identified clear sky from April 1994 IOP.

areas of thin cirrus to the north and south from the horizon to about 10-15° above from 1340 to 1620 GMT. The presence of the cirrus at these zenith angles also has little effect on the SW measured due to the cosine response of the instrument. In addition, the hourly average WSI cloud fraction decreases from about 7% for the 14th hour to less than 1% the following hour, even though visual inspection of the images do not reflect this dramatic change. The apparent size of the circumsolar disc does decrease during this time. All other periods identified as clear by the detection method show cloud fraction near zero or slightly above, with a few no greater than 1%.

Clear Sky Empirical Fit

The primary factor that determines the magnitude of the downwelling SW irradiance at any time for clear skies is the solar zenith angle. Other factors such as aerosols, surface albedo, and column water vapor amounts exhibit far less influence. Thus, it is customary to empirically fit clear sky irradiance using the cosine of the solar zenith angle as the independent variable. The form of the function can be as simple as a linear fit (Cess et al. 1995) or can be more complex, such as a series of polynomials (Waliser et al. 1995). Given the uncertainties inherent in total and diffuse SW measurement, a simple equation such as

$$Y = a^{b(1)} \qquad (1)$$

works well for zenith angles less than 75 - 80° (> 0.15). This is the form of equation chosen for the following empirical fits, where Y is the total SW clear sky irradiance or diffuse ratio, as the case may be, and a and b are regression coefficients.

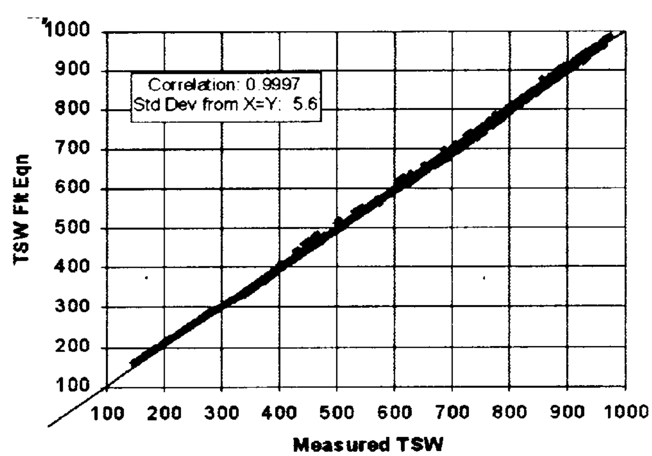
The regression coefficients are determined using a sum-of-least-squares robust estimation that minimizes the sum of the absolute deviations. Thus outliers due to mis-identification of clear sky irradiance measurements are eliminated from the calculation. As a limitation, this method requires a minimum number of measurements identified as clear to insure a statistically robust calculation. For our regressions, a minimum of 120 1-minute clear measurements was set as the required limit. If at least 120 measurements are identified as clear on a given day, daily regression coefficients are possible. Regression coefficients are then calculated for both the total SW and the diffuse ratio. In this way, both total and diffuse (and by subtraction, the direct) clear sky SW irradiances can be estimated. Table 1 lists the coefficients calculated for the April 1994 IOP for the BSRN SW radiometers for days meeting the minimum limit.

Table 1. Daily a & b regression coefficients for equation (1) for the diffuse ration (DifRat) and total SW irradiance (Tot SW) for clear skies. N is the number of 1-minute measurements identified as clear for that day.

940401	0.1013	-0.7710	1125.1	1.2924	311
940403	0.0843	-0.8008	1130.8	1.2408	372
940406	0.0879	-0.9011	1152.2	1.2631	230
940413	0.0792	-0.8453	1134.9	1.2678	199
940415	0.1215	-0.6793	1108.0	1.2403	224
940416	0.1008	-0.7784	1097.6	1.2563	381
940417	0.1025	-0.7660	1087.7	1.2541	354
940418	0.1081	-0.829	1092.5	1.2494	151
940426	0.1229	-0.7250	1099.2	1.2706	410

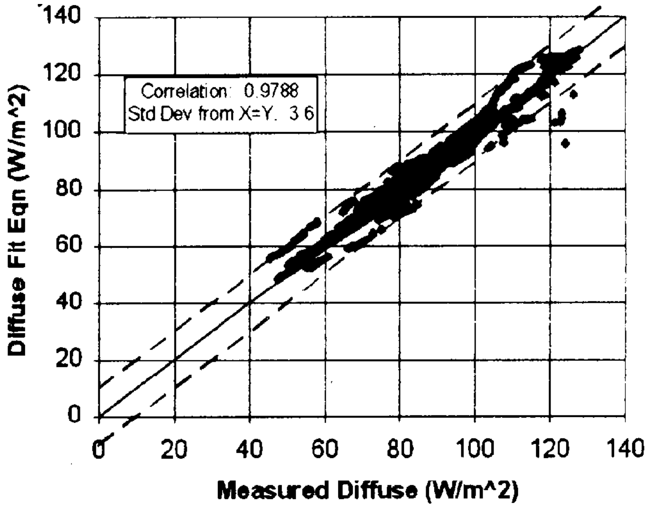
Figure 2a shows a comparison of identified clear sky total SW irradiance measurements to the corresponding empirical fit values. The correlation (0.9997) and standard deviation from perfect agreement (5.6 Wm^{-2}) both indicate the high degree of accuracy achieved by the method. For the diffuse irradiance (Figure 2b) the correlation, though considerable, isn't as large (0.9788).

There is larger error in this estimate, partly because the clear diffuse irradiance is calculated using both the diffuse ratio coefficients and the clear sky fit irradiance. The standard



(a)

Figure 2. Comparison of clear sky measured and calculated downwelling (a) total and (b) diffuse SW irradiance. Dashed lines in (b) represent the pyranometer error range.



(b)

Figure 2. (contd)

deviation is less (3.6 Wm^{-2}), due to the comparatively smaller magnitude of the diffuse irradiance. However, all deviations from perfect agreement are still primarily within the nominal pyranometer error range of 10 Wm^{-2}. An example of the calculated clear sky values, as well as measured irradiances, is given in Figure 3 for April 18th (identified as the worst case in Section 1) using the coefficients given in Table 1.

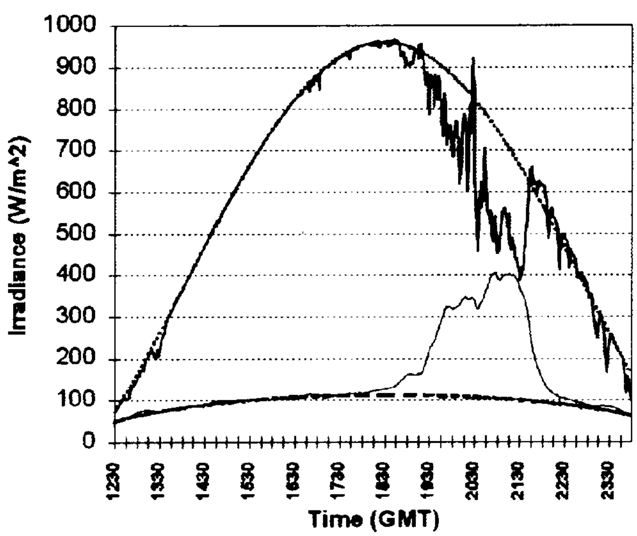


Figure 3. Calculated clear sky (dotted) and measured (heavy solid) total SW, as well as clear (dashed) and measured (solid) diffuse SW, for April 18th, 1995 at the ARM SGP central facility.

SW Cloud Forcing

Negative cloud forcing values denoting a decrease in energy to the surface due to the presence of clouds. Using the empirical fits discussed above, the downwelling SW cloud forcing has been calculated for April 1994 at the central facility. Since only days in which at least 120 1-minute measurements were identified as clear sky were used to calculate the coefficients, some method must be used to estimate these coefficients for the other days. Both Cess et al. (1995 and Waliser et al. (1995) used coefficients that represented an average over the entire data series, primarily due to infrequent clear sky data. Since in the present case it was feasible to determine coefficients representing certain days, it is possible to either determine average coefficients for the entire month, or interpolate the coefficients between known days. The series of values given in Table 1 suggest that perhaps the latter method would give more accurate results, considering the change in magnitude of the total SW a coefficient from the first to second half of the month due to calibration drift of the pyranometer.

Figure 4 shows the daily (24 hour) average cloud forcing results. The days with the largest negative total SW cloud forcing (5th, 10th, and the 29th) also exhibit slightly negative cloud forcing in the diffuse irradiance as well. The daily average total SW values show that these days were heavily overcast. All other days show that the loss of SW energy at

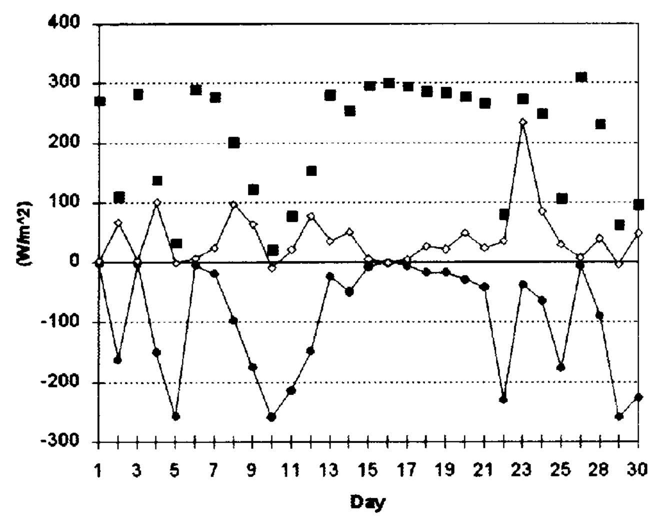


Figure 4. Daily average total (circles) and diffuse (diamonds) SW cloud forcing for the April 1994 IOP. Squares denote the average measured total SW. Note: 27th excluded due to missing data.

the surface is due to attenuation of the direct SW component, and that the diffuse irradiance mitigates the energy loss.

The clear sky detection and empirical fitting techniques have also been applied to data collected at the SGP central facility during the recent Atmospheric Radiation Measurement Program Enhanced Shortwave Experiment (ARESE). In this case, data from three different radiometer packages are available. These include the Solar and Infrared Observing System (SIROS), a rotating shadow-arm instrument prototype (RSR) under development at Penn State University, and the BSRN instruments. Figure 5 gives the total SW daily cloud forcing averages for October 1995 for the three systems.

Instrument inter-calibration offsets exhibited during this period between the three systems and differences in data logging techniques produced standard deviations from perfect agreement of up to 29 Wm^{-2} for the total SW 1-minute data under clear sky conditions, and 25 Wm^{-2} for 30-minute averages. For all-sky, which includes cloudy periods, the standard deviations increased to 57 Wm^{-2} for the 1-minute data (Long 1996). Despite these differences, the algorithm produced very similar cloud forcing results for all three systems. The standard deviations from perfect agreement between RSR and SIROS (4.0 Wm^{-2}), RSR and BSRN (6.7 Wm^{-2}), and SIROS and BSRN (5.1 Wm^{-2}) are less than the calibration offsets. This is not surprising since the clear sky irradiance is a fit to the detected clear sky measurements of each system, which include the offset. Since the cloud forcing is determined by differencing, the offset is mostly subtracted out.

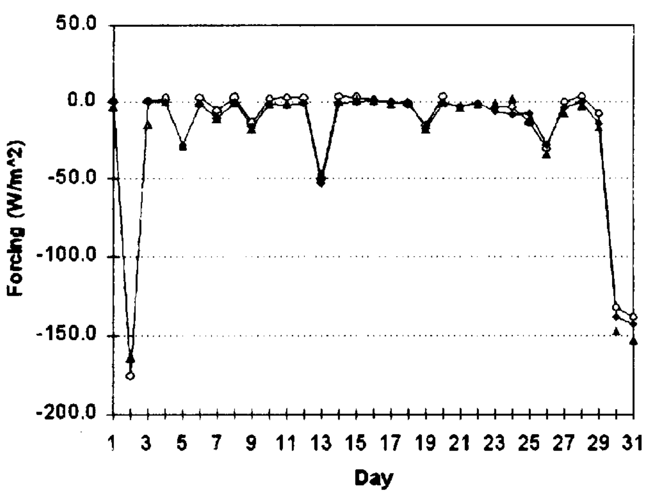


Figure 5. Daily average total SW cloud forcing for October 1995 derived from Penn State RSR (open circles), SIROS (diamond), and BSRN (triangle) data.

Summary

We have developed a method to estimate clear sky SW irradiances and diffuse ratio given only measurements of the downwelling total and diffuse irradiance. Thus ancillary data (such as that used as input for model calculations) are not needed. As such, current and past diffuse and total SW data sets can be quickly processed to produce cloud forcing results. The entire procedure can be automated and included in ARM site data products for release to the scientific community. In addition, methods are currently under development to use the clear sky and measured diffuse ratio time series to estimate cloud fractions and cloud type.

The clear sky detection method has been verified using both WSI cloud fraction data and images. A limitation of the empirical fit algorithm, for daily estimates, is the need for a statistically significant number of identified clear sky measurements during a diurnal cycle. For 1-minute data, 120 measurements has been found to produce good results. Given the clear sky irradiance, surface SW cloud forcing has been calculated for both the April 1994 IOP and the recent ARESE experiment. While only daily averages are given here, the cloud forcing is available at 1-minute resolution for both experiments. It has been shown that the method, unlike model calculations of clear sky SW irradiance, is largely independent of instrument calibration offsets.

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