JP2.5 A CLIMATOLOGY OF SHORTWAVE CLOUD RADIATIVE FORCING USING GROUND-BASED BROADBAND RADIOMETRIC TIME SERIES

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1. INTRODUCTION

Clouds significantly affect shortwave (SW) radiation incident on the surface of the Earth. Cloud effects on surface SW irradiance are linked to changes in the surface and atmospheric heating rates, which result in variations in the evolution of the weather and climate (Wielicki et al., 1995). Shortwave cloud effect is defined as the difference between the measured SW irradiance and an estimate of the SW irradiance that would be measured if clouds were not present, i.e., clear-sky. One method to compute the clear-sky SW irradiance is to use a radiative transfer model. Errors in vertical profiles of water vapor and aerosol amounts, combined with uncertainties in aerosol properties, leads to errors in the calculated clear-sky SW irradiance.

An alternative approach for estimating clear-sky SW irradiances is directly from measured time series of total, diffuse and direct SW irradiances. Errors in the clear-sky SW irradiances are now associated with measurement errors and uncertainties in the method used to infer clear-sky SW irradiance from the time series. Several approaches have been implemented for calculating the SW cloud effect directly from radiometric measurements (Duchon and O'Malley, 1998; Long and Ackerman, 2000; Marty and Philipona, 2000). The approaches of Marty and Philipona (2000) and Duchon and O'Malley (1999) use ancillary data such as screen temperature, relative humidity and a database of absorption line strengths to separate SW irradiance measurements into those taken under clear and cloudy skies. The approach of Long and Ackerman (2000) differs from these other two approaches because it uses only SW irradiance data to separate the data into periods of clear and cloudy skies. On days which have a sufficient amount of correctly distributed clear-sky data a curve is fit to the clear-sky SW irradiance data. The clear-sky SW irradiance curve parameters are then interpolated from sufficiently clear days to cloudy days, thereby allowing the SW cloud effect to be computed for all days.

The Long and Ackerman (2000) algorithm was initially developed to use SW irradiance measurements averaged over 1-minute or less. The algorithm is modified to allow use of data averaged up to 15 minutes. This allows the SW cloud effect to be computed for several long term SW irradiance time series located in diverse climatic regimes that were not archived at 1-minute resolution. We created a database of the SW cloud effects and then used them to explore relationship between the SW cloud effect, monthly precipitation and diurnal temperature range.

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2. METHODS

Figure 1 maps the geographic location of stations used in this study, and Table 1 summarizes general information about them. We screened data used in this study according to several criteria. First, time series of any two of the total, the direct and the diffuse shortwave (SW) irradiances must be available because any of the quantities can be computed using the other two. Second, at least one year of data should be available so that we can compute seasonal means. Third, if the averaging interval sample standard deviations are not available, then the data may be averaged up to 5 minutes, but if the standard deviations are available then the data may be averaged up to 15 minutes. Without the averaging interval sample standard deviations, the data is limited to 5 minutes so that a standard deviation of the SW irradiances can be computed over a 15-minute interval. Data averaged longer than 15 minutes is not used because sky cover can change appreciably after 15 minutes.

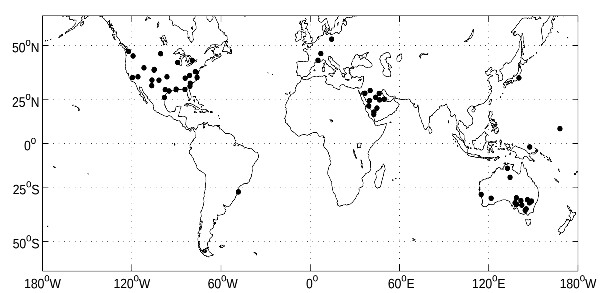

FIG. 1: Geographic distribution of stations. Each station is denoted with a black dot.

The Long and Ackerman (2000) algorithm uses four tests to separate SW irradiances measured under clear skies from those measured under cloudy skies. Two tests compare the magnitude of the total and diffuse SW irradiances with set limits, and the other two tests compare the variability of normalized total and diffuse SW irradiances with set limits (Long and Ackerman, 2000). Figure 2 illustrates that clouds tend to increase the variability and

Location	North America	Saudi Arabia	Australia	Global
Number	26	11	14	7
Lat.	47.68°N 26.20°N	29.79°N 16.90°N	14.53°S 36.74°S	NA NA
Long.	122.25°W 76.25°W	36.61°E 49.48°E	114.71°E 147.21°E	NA NA
Elevation	1829m 4m	2039m 4m	385m 10m	491m 6m
Archive	15 yr	2 yr	4 yr	7 yr
Data Average	15 min. 1 min.	5 min. 5 min.	1 min. 1 min.	3 min. 1 min.
Köppen Climate	B, C, D	B	A, B	A, C, D

Table 1: Summary of stations used in this study. For each region, the range of latitude, longitude, elevation and data averaging time are provided, as is the length of the longest time series. The last row lists the Köppen climate types (Trewartha and Horn, 1980) in each region. Translation of Köppen climate types: A - tropical humid climate; B - dry climate; C - subtropical climate and D - temperate humid climates. The fifth column, labeled "Global", denotes stations that are scattered around the Earth, and so latitude and longitude ranges are not applicable.

change the magnitude of SW irradiances compared with clear skies. The two magnitude tests are not affected by increasing the averaging time of the SW irradiance data, whereas the two variability tests are affected. For each of the variability tests, the limits were modified by averaging 1-minute SW irradiance data collected at Payerne, Switzerland, during 1994 over two, three, five, ten and fifteen minutes, and then adjusting the limits until similar results were observed using the modified and the Long and Ackerman (2000) algorithm.

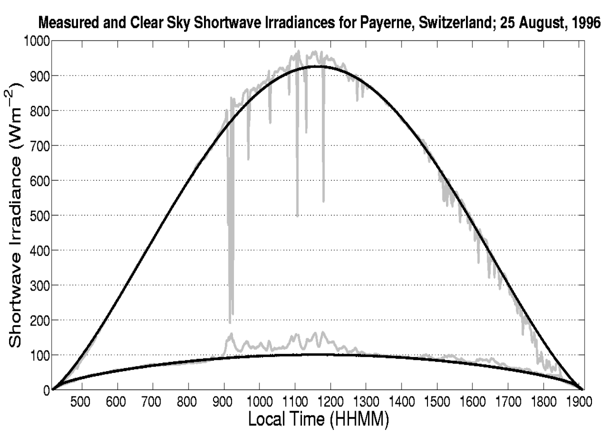

FIG. 2: Measured total SW irradiance (upper gray curve), estimated clear sky total SW irradiance (upper black curve), measured diffuse SW irradiance (lower gray curve) and estimated clear sky diffuse SW irradiance (lower black curve), for Payerne, Switzerland on 25 August, 1996.

The modified algorithm was evaluated against the Long and Ackerman (2000) algorithm using SW irradiance data measured at Payerne, Switzerland during 1996. One-minute data were averaged over two, three, five, ten and fifteen minutes, and averaging interval sample standard deviations were calculated for data averaged over five, ten and fifteen minutes. For days mutually fit by the Long and Ackerman (2000) and the modified algorithm, the standard deviations of clear-sky total and diffuse SW irradiances were at most 9 Wm^{-2} and 5 Wm^{-2}, respectively. These errors result from incorrectly separating SW irradiances taken under clear and cloudy skies. To estimate errors produced by interpolating clear-sky SW irradiance curve fits to cloudy days, time series of the absolute percent errors between daily means of clear-sky SW irradiances were computed. Absolute percent error is defined as $|I_n - I_1|/I_1$, where I_1 is the daily averaged clear-sky SW irradiance yielded from the Long and Ackerman (2000) algorithm using 1-minute data and I_n is daily averaged clear-sky SW irradiance yielded from the modified algorithm using two through fifteen minute data. At some locations, e.g. the tropical western Pacific, days with sufficient correctly distributed clear-sky periods are infrequent, and so clear-sky curves are infrequently fit. For these locations, we can use all of the clear-sky SW irradiances from a longer period, e.g., a month, to fit a clear-sky SW irradiance curve. The errors introduced by using this procedure is also assessed.

Interpolating clear-sky SW irradiance curve fit parameters to cloudy days throughout the year causes the interquartile range of the absolute percent error of the total and diffuse clear-sky SW irradiances to be at most 1% and 16%, respectively. Fitting clear-sky SW irradiance curves to clear-sky SW irradiances from a month causes the interquartile range of the absolute percent error of the total and diffuse clear-sky SW irradiances to be approximately 2% and 18%, respectively. The absolute percent error increases when fitting clear-sky curves over a month of data because combining clear-sky data from several days removes day-to-day variations of clear-sky SW irradiances that occur when using interpolation. Because the absolute percent errors introduced by the modified clear sky algorithm are relatively small, the algorithm was applied to SW irradiance time series measured at the stations described in Table 1 to yield time series of SW cloud effect.

3. RESULTS

The effect of clouds on the downwelling shortwave (SW) irradiance at the surface of the Earth is examined using the SW cloud-effect ratio. The SW cloud-effect ratio is defined to be the ratio of measured total to clear-sky SW irradiance. A SW cloud-effect ratio less than 1.0 denotes the location received less total SW irradiance than would have been measured under cloud-free conditions and a SW cloud-effect ratio greater than 1.0 denotes that a location received more total SW irradiance than would have been measured under cloud free conditions. Positive SW cloud-effect ratios are illustrated in Figure

2 between 10:00 and 13:00, when measured total SW irradiances were greater then the clear-sky total SW irradiances. The SW cloud-effect ratio is used because it removes most of the diurnal and seasonal cycles inherent in the standard definition of surface SW cloud forcing, which is measured total SW irradiance minus clear-sky total SW irradiance.

The seasonal sample means of SW cloud-effect ratios were grouped by Köppen climate types and are presented in Table 2. The seasonal means tend to follow the Köppen climate types reasonably well with stations in arid and semi-arid climate types having the largest SW cloud-effect ratios and stations located in climates with wet winters and dry summers having SW cloud-effect ratios increasing during summers and decreasing during winters.

	Spring Mean	Summer Mean	Autumn Mean	Winter Mean
Af	0.74	0.74	0.73	0.71
BS	0.83	0.82	0.84	0.84
BW	0.88	0.93	0.93	0.86
Cf	0.70	0.73	0.73	0.69
Cs	0.74	0.82	0.76	0.67
Df	0.64	0.71	0.66	0.60

Table 2: Summary of seasonal means of SW cloud-effect ratios computed at the stations described in Table 1. The first row lists the Köppen climate types (Trewartha and Horn, 1980) in each region. Translation of Köppen climate types: Af - tropical wet; BS - semi-arid; BW - arid; Cf - subtropical with no distinct rainy season; Cs - subtropical with wet winter and dry summer and Df - temperate with no distinct rainy season.

Besides knowledge of the seasonal means of SW cloud-effect ratios one would also like to understand how the means were realized, so histograms of seasonal SW cloud-effect ratios are presented in Figure 3. The histograms of SW cloud-effect ratios at Toronto, Canada (Figure 3a), which is located in a “Df” type climate, illustrates the effect of the frequent extra-topical cyclones that pass over the station between September and May. These cyclones produces extended periods of stratiform clouds which frequently cause small SW cloud-effect ratio (<0.25). Between June and August the number of cyclones passing over Toronto are reduced and the occurrence of small cloud-effect ratios also decrease. At Bendigo, Australia (Figure 3b), which is located in a “Cf” type climate, the histograms illustrate that the frequency of SW cloud-effect ratio is distributed differently than at Toronto. In particular, the frequency of small SW cloud-effect ratios are much less and there is a small second mode around 0.45, between June and August, which can be attributed to extra-tropical cyclones passing over the station.

Figure 3c illustrates histograms of SW cloud-effect ratios at Katherine, Australia, which is located in a tropical wet and dry type climate, Köppen climate type “Aw”. The distributions of SW cloud-effect ratios change from being frequently near 1.0 between June and August, the dry season, and SW cloud-effect ratios that are distributed more towards smaller values between December and February, the wet season. The distribution of SW cloud-effect ratios between December and February at Katherine are typical of stations that frequently experience convective type clouds. Comparison of the histograms suggest that the type of cloud, in addition to cloud amount and height, interacting with SW irradiance can cause quite different distributions of SW irradiance incident at the surface of the Earth.

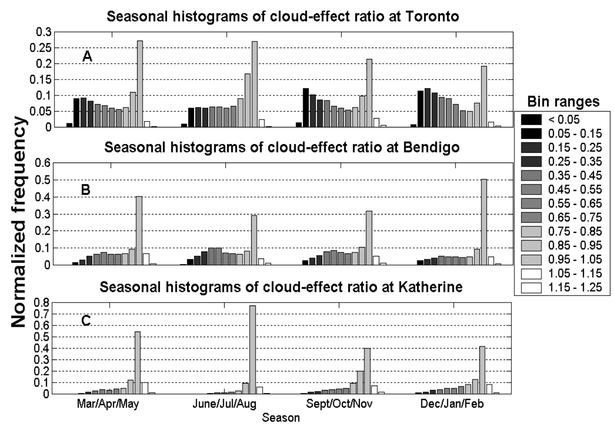

FIG. 3: Seasonal histograms of SW cloud-effect ratio at A) Toronto, Canada, B) Bendigo, Australia and C) Katherine, Australia. Fifteen-minute averages of cloud-effect ratio are used to create the histograms. The shading represents bins of SW cloud-effect ratio with a width of 0.1.

To explore the relationship between monthly mean SW cloud-effect ratio, monthly precipitation, and diurnal temperature range, we computed the Spearman rank correlation (Wilks, 1995). The Spearman rank correlation was used because it is insensitive to outliers, allows for non-Gaussian data distributions and requires only a monotonic relationship of the variables.

Figure 4 illustrates that ”A” and ”B” Köppen climate types yield significant large negative correlations between monthly mean SW cloud-effect ratio and monthly precipitation, which suggests that when radiative important clouds are present they precipitate. For ”C” and “D” Köppen climate types the correlations are more variable, ranging from strongly negative correlation at Hanford, California, to no correlation at Lindenberg, Germany. The lack of correlation at Lindenberg, Germany, Madison, Wisconsin, and Bismarck, North Dakota is caused by the lack of correlation between sky cover and precipitation, 0.28, -0.07 and -0.11 at Lindenberg, Bismarck and Madison, respectively.

The correlations between monthly mean SW cloud-effect ratio and diurnal temperature range are varied (not shown) but generally are positive, implying that when

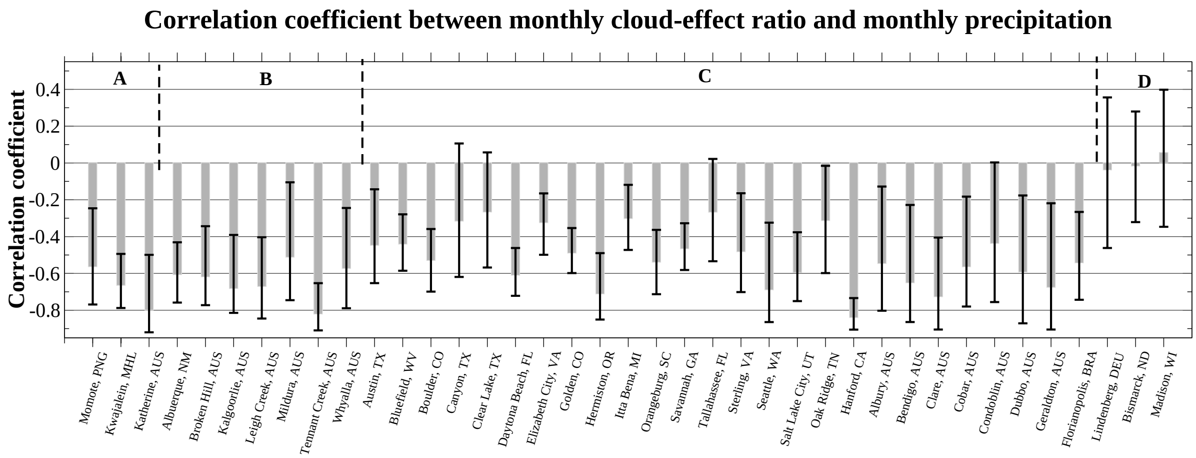

FIG. 4: Spearman rank correlation (gray bars) between monthly mean SW cloud-effect ratio and monthly total precipitation of stations used in this study. The black bars mark the range of the 95% confidence interval of the correlation. The letters A, B, C, and D refer to Köppen climate type.

more of the possible clear-sky SW irradiance is incident at the surface of the Earth the temperature range is larger.

4. CONCLUSIONS

Quantifying the effect of clouds on surface shortwave (SW) irradiance is important for the study of energy transfer through the Earth system. The Long and Ackerman (2000) algorithm uses only time series of surface radiometer measurements to calculate clear-sky SW irradiances and consequently SW cloud effect. The algorithm was modified to use data averaged up to five minutes, if the averaging interval sample standard deviation are not provided, and up to fifteen minutes if the averaging interval sample standard deviations are provided.

The modified algorithm produced small absolute percent errors relative to the Long and Ackerman (2000) algorithm and so was used to produce time series of SW cloud-effect ratios for several station located in various Köppen climate types. The Spearman rank correlations calculated between monthly means of SW cloud-effect ratio, monthly precipitation, and diurnal temperature range. The SW cloud-effect ratio negatively correlates with precipitation and generally positively correlates with diurnal temperature range.

The database of SW cloud-effect ratios produced in this study provides useful diagnostics for satellite retrievals of SW cloud effect and calculations of SW cloud effect in atmospheric general circulation models. In an atmospheric general circulation model, the correlations between SW cloud effect, precipitation and diurnal temperature range noted in this study can be used to diagnose interactions between SW radiation and cloud parameterizations. Besides the utility of the SW cloud-effect ratio database for diagnostics, it can also be used to explore further the relationship between SW cloud effect and cloud properties such as cloud height, cloud thickness, and horizontal cloud spacing.

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