Diurnal evolution of solar radiation at the surface in the city of São Paulo: seasonal variation and modeling

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Summary

Seasonal variations in the diurnal evolution of the global, diffuse and direct solar radiation at the surface, the clearness index, diffuse fraction and direct fraction are described in detail for the City of São Paulo, Brazil. The description is based on measurements of global and diffuse solar radiation carried out over 5.25 years. The diffuse component was measured with a shadow-band device. The annual evolution of the amplitude of the diurnal cycle of all radiometric parameters indicates a seasonal pattern with two distinct periods: autumn-winter and spring-summer. About 10% of the observed period was characterized by clear sky days. This seasonal variation is determined by a larger incidence of clear sky days in the autumn-winter period. Reductions of up to 10% in hourly and daily values of global radiation were observed in conjunction with an increase in particulate matter concentration on clear sky days. The pollution effect may be responsible for the discrepancy, of 16%, found between local and more regional estimates of global solar radiation in São Paulo. The diurnal evolution of hourly values of monthly-averaged global and diffuse solar radiation were successfully estimated by the empirical expressions derived here. Daily values of monthly-averaged global solar radiation were satisfactorily estimated using the Angstrom expression.

1. Introduction

Knowledge of the seasonal evolution of global, diffuse and direct solar radiation, at the surface, is important for climate studies, solar collector efficiency estimation, and agricultural and several meteorological applications (Izimo and Aro, 1999; Iqbal, 1983; Duffie and Beckman, 1980). Unfortunately, these quantities are not available, at the required spatial and temporal resolution, for Brazil. With most of its territorial area (8.547 million km²) located in equatorial and tropical latitudes, Brazil has a very sparse solarimetric network. For instance, Pereira et al. (1996) reported only 22 ground stations with global solar radiation measured directly or estimated from sunshine hours. In addition, there is no available information in the literature about the diurnal evolution of global, diffuse and direct solar radiation, at the surface, and their seasonal variation for any location in Brazil. The importance and difficulties of estimating the hourly distribution of solar radiation have been emphasized by Aguiar and Collares-Pereira (1992).

The major reason for the lack of direct measurements of diffuse and direct components of the solar radiation, at the surface in Brazil, is that these parameters require special instruments such as sun-tracking pyrheliometers or occulted pyranometers with shadow-bands or disks. These apparatus are expensive, difficult to operate on a regular basis and require the use of correction factors in order to compensate for the distortion...
effects caused by the blocking device (Le Baron et al., 1990).

Due to the operational problems described above, most of measurements available in Brazil are carried out in urban areas. This is not only peculiar to Brazil, it happens in other parts of the world (Longueto et al., 1992). Direct measurements of global, diffuse and direct solar radiations based on pyranometers, pyrheliometers and other similar sensors are likely to be affected by the urban environment. For instance, air pollution may either modify the performance of sensors or alter the radiative properties of the urban atmosphere. Therefore, any application that requires extrapolation of local solar radiation measurements beyond urban limits will also have to take into consideration the role played by urban effects (Petterson et al., 1978; Oke, 1982).

To investigate the inherent difficulties associated with the operation of solar radiation measurements in a regular basis and to identify the effects caused by the urban environment on the spatial representativeness of these measurements, an experimental site was set up in the City of São Paulo (Oliveira et al., 1996). At this site, measurements of global and diffuse solar radiations have been taken regularly since April 1994. These measurements follow WMO recommendations (WMO, 1971) and have been carried out by using a fully automatic data acquisition system. The diffuse component of solar radiation, at the surface, has been measured by a shadow-band device (Mello, 1993; Escobedo et al., 1997).

The City of São Paulo, with 10 million habitants, together with 38 other smaller cities, form the Metropolitan Region of São Paulo (MRSP). This region is occupied by 16.5 million habitants distributed over an area of 8051 km² and it is the largest urban area in South America and one of the 10 largest in the world. Therefore, it is an ideal place to investigate the role played by the urban environment on solar radiation.

The MRSP, with more than 4 million motor vehicles (CETESB, 1999), is characterized as having moderate degree of contamination by particulate matter and other pollutants (Kretzschmar, 1994). Oliveira et al. (1996) detected a reduction of up to 18% in the direct beam associated with a progressive increase in the concentration of particulate matter during a period of five cloudless days in the City of São Paulo. According to the authors, depletion of the direct beam was partially compensated by an increase in diffuse solar radiation at the surface. The long-term effects caused by particulate matter on the solar radiation field in São Paulo are still not known.

To characterize the seasonal variation of hourly values of global, diffuse and direct components of solar radiation, at the surface of São Paulo City, a solar radiation dataset with 5.25 years of measurements is used.

The seasonal variations in the diurnal evolution of global, diffuse and direct solar radiations, at the surface, are presented in detail in this work because no similar scientific information about São Paulo City, is available in the literature. It is hoped that this information will improve understanding of the behavior of the solar radiation field in other urban subtropical areas.

A description of the seasonal variation of the clearness index, diffuse and direct fractions is also included here, once these quantities have been intensively applied to develop correlation models to estimate diffuse solar radiation at the surface (Liu and Jordan, 1960; Collares-Pereira and Rabl, 1979; Erbs et al., 1982; LeBaron and Dirmhirn, 1983; Soler, 1990; Satyamurt and Lahiri, 1992; Garrison and Sahami, 1995; Jacobides et al., 1996).

Special effort has been applied to quantify the impact caused by: (a) the aging effect of the pyranometers (8-years old) on all measurements of solar radiation; (b) the blocking effect caused by the shadow-band device applied to measure diffuse solar radiation and (c) the effects of particulate matter on the global and diffuse solar radiation. These effects are particularly important for understanding solar radiation measurements carried out in other urban environments where air pollution may affect the performance of the sensors and modify properties measured systematically by them.

Another motivation for this work concerns energy production and its associated environmental impact. The energy consumption in the MRSP is around 40TWh per year (Eletropaulo, 1999). This is a significant fraction of all energy produced in Brazil and it is generated basically by hydroelectric power plants. To increase production of energy, Brazil is looking for other sources of energy because the available hydroelectric