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Minute resolution estimates of the diffuse fraction of global irradiance for southeastern Australia

N.A. Engerer *

Fenner School of Environment and Society, The Australian National University, Canberra, Australia
National ICT Australia, Canberra Research Laboratory, Canberra, Australia

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Abstract

Separating global horizontal irradiance measurements into direct and diffuse components has been vigorously discussed over the past half-century of solar radiation research leading to the creation of many models which attempt to compute these components with varying degrees of success. However, over the course of this discussion, nearly all studies have focused on hourly values, with no studies that have proposed a model for minute-level values of irradiance. As data-logging technologies have become much more prolific and their storage capabilities much larger, solar radiation monitoring sites are more commonly logging data at intervals much less than one hour, but no models exists that are designed to separate these measurements into direct and diffuse components. In Australia, the Australian Bureau of Meteorology and the Australian Solar Institute have compiled a dataset of tens of millions of one-minute global, direct and diffuse solar irradiance observations, comprising data from regions all around Australia. This dataset provides a unique opportunity to investigate the relationships between global irradiance and its direct and diffuse components at higher resolution than has previously been possible. Herein, the largest and most complete diffuse fraction model analysis yet undertaken for Australian solar radiation data, and the first ever to focus on minute resolution data is reported. Nine of the most prominent diffuse fraction, or "separation", models are tested against minute resolution radiation data from three datasets. The first removed cloud enhancement events in accordance with practices undertaken by the majority of studies in the literature. The second retains these events in order to assess which model would be best suited for operational purposes. The third consisted of only clear sky observations, in order to assess the performance of diffuse fraction models under clear skies. Through the course of this study only the Perez model was found to perform satisfactorily for minute resolution data at sites in southeastern Australia. Three new diffuse models proposed in this study, one trained for each of the three datasets, were found to greatly exceed the performance of existing modeling techniques, with slight improvements over the Perez model.

Keywords: Solar radiation; Diffuse fraction; Radiation model; Cloud enhancement; Validation; DNI

1. Introduction

The most common broadband solar irradiance measurement is global horizontal irradiance (E_{gh}). This measurement records all of the solar radiation impinging on a horizontal surface as received from the skyward hemisphere, thereby including both beam (direct) radiation, which is received directly from the sun, as well as diffuse radiation, that which is scattered and reflected by atmospheric constituents and neighboring surfaces. Most often, the horizontal beam component is referred to in its normal component form (E_{bn}) also commonly entitled direct normal irradiance (DNI), whereas the diffuse radiation is

* Address: Fenner School of Environment and Society, The Australian National University, Canberra, Australia.
E-mail address: nicholas.engerer@anu.edu.au
URL: http://nickengerer.org.

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only referred to in its horizontal form (E_{dh}). Combining these components gives the fundamental closure equation for global horizontal irradiance, denoted as:

$$E_{gh} = E_{bn} \cdot cos(\theta_z) + E_{dh} \quad (1)$$

where θ_z is the solar zenith angle.

Although both of these components are included in the E_{gh} measurement, they must be handled separately in the modeling of solar energy applications. For example, concentrating solar power technologies that require reflection of solar radiation to a central receiver, such as those in the parabolic troughs or single tower designs, are primarily concerned with the beam component of radiation (e.g. Hinkley et al., 2013). In solar photovoltaic (PV) technologies, which are most often tilted, the radiation arriving on a non-horizontal surface cannot be determined accurately without explicit knowledge of the beam and diffuse components of radiation available, as they are modeled differently (e.g. Reindl et al., 1990b). These components must also be separated in studies sensitive to photosynthesis (Spitters et al., 1986) and in the design of buildings (Lam and Li, 1996), which serves to further highlight their importance.

However, directly measuring beam and diffuse components of radiation is quite costly. Beam radiation measurements are taken by a pyrheliometer device that is mounted on a sun tracker so that it can be directly pointed at the solar disc. Diffuse radiation measurements are either taken by a pyranometer fitted with a shadowball device mounted atop a sun tracker unit, or by a shadowband. These devices are expensive as they require sensitive equipment, are fitted atop moving parts and require routine maintenance, cleaning and cross-calibration (Stoffel and Reda, 2008). Such sites can easily cost over $30 K USD to install. In comparison, research grade pyranometers are cheap ($1–5 K USD), and are fixed with no moving parts, thus requiring much less maintenance with a complete installation with data logger easily costing less than $5–10 K USD. For these reasons, horizontally mounted pyranometers have become a standard radiation measurement, and E_{gh} the most readily available type of standardized solar radiation data globally.

Yet, as previously mentioned, knowledge of the beam and diffuse components of radiation are often required. Thus, a great deal of scientific literature in the field has been focused on creating models which can separate E_{gh} observations into their horizontal beam (E_{bh}) and horizontal diffuse components. Therefore, it is appropriate to begin with a review of such approaches, which are referred to interchangeably in the literature as decomposition or separation models. This study will adopt the latter terminology for the duration of this work and will focus on a diffuse fraction (K_d) modeling validation.

1.1. Review of available models

Here, the breakdown proposed by Lanini et al. (2010) is adopted, introducing the K_d models in three foundational categories: polynomial, exponential and logistic.

1.1.1. Polynomial models

The majority of K_d models operate by breaking up the relationship between K_d and the clearness index (K_t) into fitted polynomials in a piece-wise fashion. This approach stemmed from the relationship between K_d and K_t first discussed by Liu and Jordan (1960) who investigated the relationship between global and diffuse irradiance at daily intervals in Blue Hill, Massachusetts. Using this relationship as applied to hourly data recorded in Canada, Orgill and Hollands (1977) first suggested modeling K_d with a piece-wise function in terms of K_t. This approach was further refined by Erbs et al. (1982) for locations in the United States. Each of them requiring only K_t as an input. For the purposes of clarity, note that K_d and K_t are defined as:

$$K_d = \frac{E_{dh}}{E_{gh}} \quad (2)$$

$$K_t = \frac{E_{gh}}{E_{ext_h}} \quad (3)$$

where E_{ext_h} is the horizontal component of extraterrestrial radiation

However, later research studies noted that these models did not accurately represent the spread in the K_d for given values of K_t (e.g. see Fig. 4), and thus they began to include additional variables. Skartveit and Olseth (1987), Bugler (1977) and Iqbal (1980) incorporated the solar altitude (α) in order to accommodate the shift in the distribution of K_d values that occurs throughout a given day. Later, Reindl et al. (1990a) added ambient temperature and relative humidity as predictors in his K_d model in addition to the solar altitude. Both of these modifications tended to increase the accuracy of hourly K_d estimates.

Building on these works, numerous other polynomial based relationships have been generated for unique regions around the world including: Cordoba, Spain (Posadillo and López Luque, 2009); the Northern Mediterranean (De Miguel et al., 2001); Athens, Greece (Karatasou, 2003); India (Chandrasekaran and Kumar, 1994); Singapore (Hawlader, 1984); and Sao Paulo, Brazil (Oliveira et al., 2002). However, as these models are less well-known and have not been widely validated, they will not be described in further detail herein.

1.1.2. Exponential models

There are two models that complete the separation through estimation of E_{bn} first, rather than directly estimating K_d as in the polynomial models. The seminal work in this area was completed by Maxwell (1987) in the well-known DISC model (Direct Insolation Simulation Code), with a follow-on study extending this work completed by Perez et al. (1992). The considered approach was based on the Bird clear sky model (Bird and Hulstrom, 1981), wherein the deviation from the modeled clear sky K_t was modeled by an exponential fit according to air mass (AM). The DISC model required only K_t, θ_z and AM as inputs. Perez et al. (1992) added to this conceptual framework by