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ScienceDirect

Solar Energy 116 (2015) 117–124

SOLAR ENERGY

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A new correlation between global solar energy radiation and daily temperature variations

Antonio Dumas [a], Andrea Andrisani [a,*], Maurizio Bonnici [a], Giorgio Graditi [b], Gianni Leanza [b], Mauro Madonia [a], Michele Trancossi [a]

[a] University of Modena and Reggio Emilia, via Amendola n.2, Reggio Emilia 42122, Italy
[b] ENEA Portici Research Center, P. E. Fermi n.1, Portici (Naples) 80055, Italy

Received 19 February 2014; received in revised form 10 March 2015; accepted 1 April 2015

Communicated by: Associate Editor David Renne

Abstract

The energy balance for an atmospheric layer near the soil is evaluated. By integrating it over the whole day period, a linear relationship between the global daily solar radiation on a horizontal surface and the product of the sunshine hours at clear sky with the daily maximum temperature variation is achieved. The results for the monthly averaged daily values show a comparable accuracy with some well recognized models such as the Ångström–Prescott one, at least for Mediterranean climatic area. Validation of the results has been performed using old data sets which are almost contemporary and relative to the same sites with the ones used for the comparison.
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Keywords: Global daily solar radiation; Temperature based models; Atmospheric physical model; Daily temperature variations

1. Introduction

The global daily solar radiation on horizontal surface – in the following G – is one of the most critical input parameter concerning crop growth models, evapotranspiration estimates and the design and performance of solar energy systems. When a direct measurement of G is not available, global solar radiation can be estimated by means of some empirical formulas, depending on other easy-to-achieve variables. Indeed daily data of G usually present too much dispersion to be accurately fitted in this way; such relationships actually work with the monthly mean values $\bar{G}$ of G, or very often with the monthly mean values $\bar{K}$ of the clearness index $K = G/G_0$, being G_0 the extraterrestrial daily solar radiation. Among these relationships, the Ångström and the Ångström–Prescott ones are probably the most known in literature (Ångström, 1924; Prescott, 1940): they linearly relate $\bar{K}$ with the monthly mean value $\bar{S}$ of the daily fraction of clear sky $S = N/N_0$, being N and N_0 the daily sunshine and extra-atmospheric sunshine hours respectively. A similar formula to the Ångström–Prescott is the Albrecht formula, as reported by Guerrini et al. (1977); it linearly relates $\bar{G}$ with $\bar{N}$ this time. Other expressions, correlating $\bar{G}$ or $\bar{K}$ with $\bar{S}$ or $\bar{N}$ by means of non-linear expressions, exist (Barbaro et al., 1979; Akinoglu and Ecevit, 1990; Suehrcke, 2000; Suehrcke et al., 2013). In particular Suehrcke (2000) proposed a quadratic[1] expression between $\bar{K}$ and $\bar{S}$ which make use of a single physical parameter, the global solar

* Corresponding author. Tel.: +39 080 5442622.
E-mail address: andrea.andrisani@uniba.it (A. Andrisani).

[1] For daily data a cubic expression between K and S is proposed.

http://dx.doi.org/10.1016/j.solener.2015.04.002
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radiation at clear sky. See Driesse and Thevenard (2002) for a comparative study.

It is also possible to correlate $\bar{G}$ or $\bar{K}$ with the monthly mean values of the daily temperature variations ΔT, instead of sunshine durations. Such choice could be particularly useful in reconstructing past radiation data series, in improving the spatial resolution of horizontal radiation estimates and in enabling some validation and adjustment satellite based measurements. Among the various correlation models present in literature, we mention the Hardgreaves–Samani (Hargreaves, 1981; Hargreaves and Samani, 1982) and the Bristow–Campbell (Bristow and Campbell, 1984) ones, which make use of non-linear relationships.

The equation we want to propose here, even if in the same class of those relating temperature variations with global solar radiation, is somewhat different from the Hardgreaves–Samani and the Bristow–Campbell, together with their derivations. It linearly correlates $\bar{G}$ with the monthly mean values of the product $N_0 \cdot \Delta T$. This product defines a new atmospheric parameter F, called *action of temperature variation*. So in some sense our relationship can be considered as a hybrid version of the temperature-based and sunshine-based models. It was introduced by Dumas (1984), together with another relationships between $\bar{N}$ and $\bar{F}$, by means of some empirical considerations. In Section 2 of the present article we give a new physical derivation for these formulas.

This article is structured as follows. By an analysis of energy balance in a system consisting of a layer of atmosphere and a surface layer of soil adjacent to it, a relationship between the solar radiation incident on the soil's surface and the daily temperature variation of the corresponding atmospheric layer is found. The most important results about linear regression performed on data from seven Italian cities are then presented, together with error analysis. A comparison with other studies, regarding the same sites and approximately the same years, in which the Ångström–Prescott, the Albrecht and the Barbaro's formula were applied, is also reported. In the conclusions we will summarize the results obtained in this work.

2. Daily radiation modelling

It's well known that the Earth is a "cold body" like all the planets, namely it does not produce energy but it disperses into the surrounding environment, the sidereal space, the energy coming from the Sun in form of electromagnetic radiation. Actually only part of the earth's surface and atmosphere interact with solar radiation in a generic instant of time, so that even if the overall system "atmosphere-terrestrial surface" has a steady thermo-energetic budget, its subsystems may have a periodic one instead. There are fluctuations with different periods and different intensity: daily cycles, seasonal, secular. We assume that the energy fluctuation has zero average into such suitably restricted subsystem, even if this is related to the cycle with a shorter period. This cycle can be located roughly in the period of rotation of the earth around its axis, at least for not very high latitudes.

We consider a subsystem composed of a thin layer of soil, a first layer of atmosphere adjacent to it and a second higher layer of atmosphere. The first two layers have an extension and thickness such that

(a) Sufficiently small thermal inertia, of the same order of magnitude for the layers, is assumed.
(b) The layers can be considered flat and parallel.
(c) The temperature gradient is orthogonal to the layers.

Moreover, we assume that no thermodynamic transformations involving phase changes or chemical reactions and no change in pressure are present in the first atmospheric layer.

Let T_a, T_s, T_u the temperatures respectively of the air, of the soil and of the higher atmospheric layer, H_a, H_s the flux of solar energy incident on the air and the soil layers, α_a, α_s their solar radiation absorption coefficients and h, k the convention and conduction coefficients. With the above assumptions, the instantaneous energy balance for the first atmospheric layer, per unit area, is

$$\frac{\partial \varepsilon_a}{\partial t} = \alpha_a H_a - h(T_a - T_u) - k(T_a - T_s) \quad (1)$$

where the term on the left is the temporal variation of the energy content of the layer ε_a, while those on the right are respectively the solar energy absorbed and the heat exchanged per unit time by convection and conduction with higher atmosphere layers and with the soil surface. We neglect here the energy exchange by thermal radiation, since the air is almost transparent to infrared radiations, having wavelengths of about $5 - 10\ \mu m$.

Likewise, for the soil layer we have:

$$\frac{\partial \varepsilon_s}{\partial t} = \alpha_s H_s - k(T_s - T_a) + \dot{q}_c + \dot{q}_r \quad (2)$$

where $\dot{q}_r$ and $\dot{q}_c$ are the amount of energy exchanged per unit time respectively with the deeper soil layers and for infrared radiation with the sky. These quantities are assumed to be constant and their sum will be henceforth indicated with $\dot{q}_d$.

From (2) we have

$$k(T_s - T_a) = \frac{\partial \varepsilon_s}{\partial t} - \alpha_s H_s - \dot{q}_d \quad (3)$$

and inserting it into (1), we obtain

$$\frac{\partial \varepsilon_a}{\partial t} = \alpha_a H_a - h(T_a - T_u) - \frac{\partial \varepsilon_s}{\partial t} - \alpha_s H_s - \dot{q}_d \quad (4)$$

The temporal trend of the energy content of each layer depends on their thermal inertia, since they are subjected to thermal stress at the same time interval. Therefore, for the hypothesis (a), we can suppose that

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