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ScienceDirect

Energy Procedia 45 (2014) 342 – 351

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

# Dumas relationships applied to two Italian sites. A comparison among various solar energy estimating formulas.

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**Abstract**

In this paper different methods for a predictive estimation of solar radiation are compard. The timeframe is 2007-2009. The comparison has been made on two sites, Manfredonia and Portici, both located in the south of Italy. Even if these sites are relatively near and subjected to a temperate climate, typical of Mediterranean region, they present some important differences in local micro-climate, which affects atmospheric behavior, particularly in the daily temperature variations. The method for estimating solar radiation proposed by Dumas (1984) has been tested and compared with various solar radiation empirical formulas, correlating solar radiation energy with temperature, as the well known Bristow-Campbell and Hardgreaves-Samani models. This preliminary study shows the potential of the Dumas method, even in the tested locations. It also shows that the Dumas relation actually performs better then the models mentioned above, in particular for sites with low values of daily temperature variations. In some cases it even offers a comparable accuracy with respect to the Ångström-Prescott formula.


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*Keywords:* Global solar energy; Temperature based models ; Ångström-Prescott ; Hardgreaves-Samani ; Bristow-Campbel.

## 1. Introduction

A detailed analysis and evaluation of the amount of solar energy incoming on the Earth surface by means of electromagnetic radiations is nowadays of primary interest. Present demands of food and renewable energy reclaim an intensive agricultural production and the implementation of solar energy systems more and more efficient. The global solar radiation on horizontal surface at a given location - in the following $G$ - is the most critical input parameter concerning crop growth models, evapotranspiration estimates and the design and the performance of solar energy devices as well [1–3]. So various efforts have been taken in order to achieve a detailed global map of daily solar radiation's energy.

Actually, this task cannot be considered fully absolvable at present. The intensitys flux of energy coming from the Sun at the Earth's distance , the so called Solar Constant, is known to be in mean 82 $KJm^{-2}min^{-1}$ by satellite observations. With some simple calculations [4] we can take into account of the various incident angles of the solar rays on the ground and of the periodical variation of the Sun-Earth distance in order to calculate $G_0$, the extra-atmospheric

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1876-6102 
Selection and peer-review under responsibility of ATI NAZIONALE
doi:10.1016/j.egypro.2014.01.037

solar radiation on a horizontal surface. However, due to interaction of solar radiation with the terrestrial atmosphere, this amount of energy is significantly far from being available at the Earth surface, and it is subject to continuous fluctuations of various nature.

If a *pure* astronomical computation for $G$ is not suitable, on the other end a set of direct measurements of the daily solar radiation performed on the ground at different locations, covering the Earth with sufficiency density, is not available at moment. The costs of maintenance for the relative instrumental apparatus, together with the great operational difficulty in keeping their calibration, makes the number of stations that can efficiently and accurately perform this task very low. In 1999, the ratio of weather stations collecting solar radiation data relative to those collecting temperature data were calculated to be 1:100 in United States and at global scale it was predicted to be 1:500, as cited by [5]. In absence of direct measurements, $G$ is usually estimated by means of different methodologies. Some methods calculate $G$ from $G_0$ by means of physical models describing the various absorption and scattering phenomena occurring in the atmosphere, in order to determine its total transmittance [6,7]. Others [8] evaluate the total transmittance by geostationary satellite images data, making use of statistical formulas between atmospheric transmittance, surface albedo and an index of cloud coverage over a specific location; with these methods a resolution of $\approx 7\ km^2$ in constructing solar radiation maps can be achieved [9]. Satellite data are also used in combination with atmospheric physical models in order to estimate $G$ [10]. For a review of various methods which make use of satellite data we suggest [11]. Other approaches apply neural networks as well, for example by considering a minimal number of local parameters together with ancillary data from other similar sites [12]. Stochastic analysis is often employed too [13].

**Nomenclature**

| | |
|---|---|
| $G$ | Global daily solar radiation on a horizontal surface ($MJm^{-2}d^{-1}$) |
| $G_0$ | Extra-atmospheric solar radiation on a horizontal surface ($MJm^{-2}d^{-1}$) |
| $N$ | Sunshine hours ($h$) |
| $N_0$ | Extra-atmospheric sunshine hours ($h$) |
| $\Delta T$ | Daily temperature variation ($K$) |
| $F$ | Temperature variation's action ($hK$) |
| $a, b, c$ | Parametric coefficients used in various empirical formulas |
| $r$ | Correlation coefficient |
| $RMSE$ | Root mean square error |

### *1.1. Empirical formulas*

Together with the methods mentioned above, simple empirical formulas relating solar radiation with some meteorological parameters are widely used for their conceptual and computational simplicity as well as for their high efficiency and accuracy. The most known formula is the Ångström-Prescott [14,15] formula (A-P in the following)

$$\frac{G}{G_0} = a + b\frac{N}{N_0} \tag{1}$$

which relates by a linear expression the total transmittance of the atmosphere ($G/G_0$) with the fraction of sunshine hours $N$ over the extra-atmospheric sunshine hours $N_0$. The terms $a$ and $b$ are parametric coefficients depending on the location, and are usually recovered by regression's methods.

Besides A-P equation, other empirical relations, connecting $G$ with daily temperature variations $\Delta T$ – i.e. the difference between the maximum and the minimum temperatures registered on a day – are widely used and recognized. Even if the sunshine-based methods are generally believed to be more accurate [16,17], temperature-based methods are often preferred since temperature records are much more available than the sunshine ones. Among the various models present in literature, we mention the Hardgreaves-Samani (H-S) model [18,19]

$$\frac{G}{G_0} = a + b\sqrt{\Delta T} \tag{2}$$

and the Bristow-Campbell (B-C) model [20].

$$\frac{G}{G_0} = a\left[1 - \exp\left(-b(\Delta T)^c\right)\right] \tag{3}$$

Here too the parameters $a, b, c$ depend on the location for both the equations.
A not well known formula is the Dumas equation, which correlates $G$ and the product of the daily temperature variation with $N_0$. It is derived from an energy balance evaluation of the atmospheric layer near the soil ([21]), and it reads

$$G = a + bN_0\Delta T$$

or

$$G = a + bF \tag{4}$$

having defined the temperature variation's action $F$ as

$$F = N_0\Delta T \tag{5}$$

As one can see, this formula is in the same class of those relating temperature variations with global solar radiation; however it is somewhat different from the previous two exposed above, since they are linear in $G$ and $\Delta T$. Besides, it takes an important role the number of hours of extra-atmospheric insolation $N_0$, because our relation actually correlates $G$ with the product $N_0\Delta T$.
Finally, we mention another formula due to Dumas. Since there is a correlation between daily solar energy incident and effective sunshine hours $N$ – e.g. A-P equation – by (4) we deduce that there must be a linear correlation even between the sunshine hours $N$ and $F$

$$N = a + bF \tag{6}$$

We will call this the second Dumas equation.
In the following we will apply the first and the second Dumas equation to two Italian sites, Manfredonia and Portici. Years 2007-2009 are considered. Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) centers of Casaccia and Portici provided us with the data. As we will see in the following paragraph, the climate properties of these two sites allow an effective comparison between the first Dumas equations and the A-P, H-S and B-C relations mentioned above. This is the main aim of the present article.

## 2. Description of the sites

Manfredonia and Portici are two Italian cities placed in the south part of the country. This area is mainly subjected to a temperate climate typical of the Mediterranean area, characterized by mild temperatures with rainy winter and dry summer. Actually, following the Köppen-Geiger climate classification [22], Manfredonias area belongs to the Cwa zone, with a more humid weather in summer then the Csa/Csb zones which are characteristic of the Mediterranean area. Both the cities lies near on coastal zones, on the Eastern and Western side of Italy respectively, and are placed on a latitude of 41.6° N and 40.8° N.
Despite this similarity in the climate classification, there are some differences about the thermal capacity of the overlying atmospheres. For the site of Manfredonia, placed at 135 *m* over the sea level near the Gargano massif, we register wide thermal escursions during the year, while for Portici, whose experimental apparatus is placed next to the sea, temperature variations are subjected to some mitigation effects [23]. In Figure 2 the daily temperature variations of the two sites are shown. Daily, ten days averaged and monthly averaged data are cosidered. While in Manfredonia we have registered a clear seasonal path for $\Delta T$, in Portici this was almost absent. Besides the $\Delta T$ values of Manfredonia are in mean higher then those of Portici.

It is generally believed [24] that temperature-based solar energy models performs better when high daily temperature variations are present, as in the case of Manfredonia, while they lack in accurate solar energy descriptions for sites like Portici, with low values and few variations about $\Delta T$. So the choice of Manfredonia and Portici as reference sites for a comparison is significant: they represent respectively, for what concern the key-parameter $\Delta T$, the best case and the worst case scenario to test temperature-based models, with the other climate variables assuming similar values.

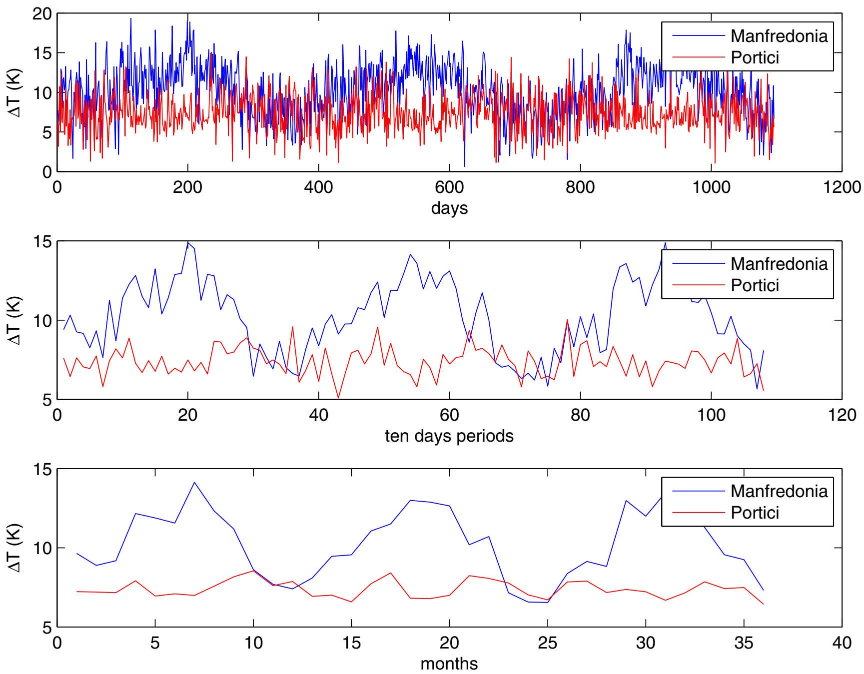


Fig. 1. Daily temperature variations $\Delta T$ for the sites of Manfredonia and Portici along the years 2007-2009. While for Manfredonia we have a typical seasonal path, the same behaviours is not registered in the case of Portici. This is not so clear for the daily values (top), but it is evident for the ten days averaged values (middle) and mainly for monthly averaged values (bottom).

## 3. Description of experimental apparatus

The data from the sites of Manfredonia and Portici was obtained with the same experimental apparatus. The global solar radiation on the horizontal surface, together with the diffuse radiation over an horizontal surface and global collimate radiation, was measured by means of three MS-802F High Precision EKO pyranometers (ISO secondary standard), while for the direct solar radiation a MS-53 EKO pyrheliometer (ISO first class) was used [23]. Both of them show a relative uncertainty of 0.5%. Temperatures was measured with a MP101 ROTRONIC thermometer, with an accuracy of $\pm 0.3°$at $20 - 25°$. About the pyrheliometer, some impurity usually deposited over its receveing surface caused an underestimated error of $20 - 30\%$, expecially for the site of Portici. Such phenomena might occurr even several times per day, making a periodic cleaning of the sensor ineffective. In order to overcome this, an estimation of the inducted error was obtained by analyzing the data of the other pyranometers, which didn't suffer of this opacity effect [23].

The flux of solar energy were measured every ten seconds (in $Wm^{-2}$) and then averaged in ten minutes intervals in order to get 144 measures per day. In order to estimate $N$, we have summed all those time intervals for which the direct solar radiation flux exceeded 120 $Wm^{-2}$, following the *WMO* standards [25]. Similarly, $G$ was obtained by integrating in one day period the fluxes of global solar radiation achieved for every ten minutes. The reported value are expressed in $MJm^{-2}d^{-1}$.

Finally, the maximum, minimum and mean temperatures were estimated for every ten minutes time intervals. Daily maximum and minimum temperatures were then obtained from these data.

## 4. Analysis of data

In studying the various models, we have considered the following groups of values for $F$ $G$, $N$, $\Delta T$ and $\sqrt{\Delta T}$

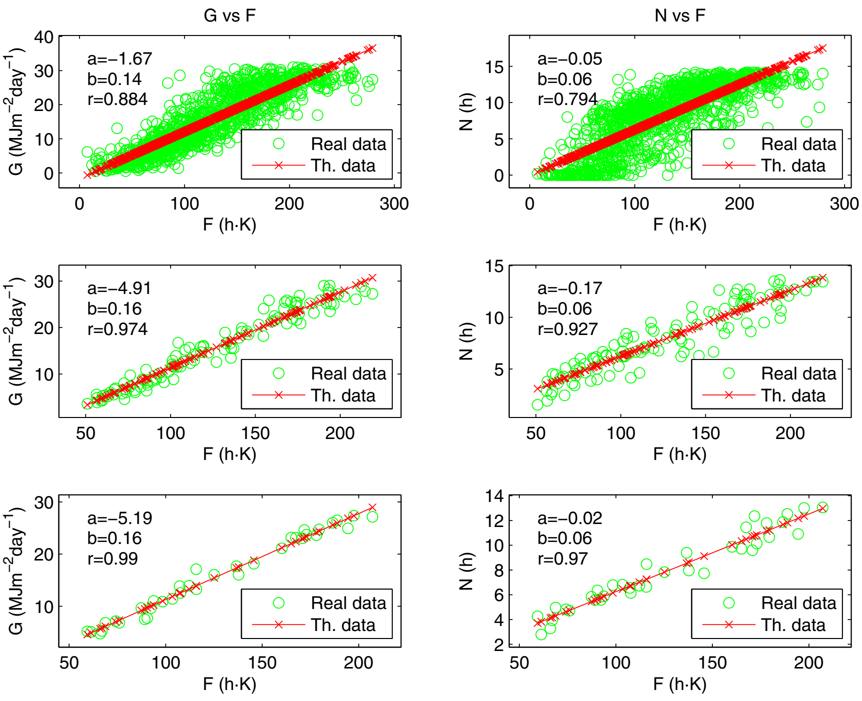


Fig. 2. $(G, F)$ and $(N, F)$ dispersion graphs for Manfredonia's site. Daily values (top), ten days averaged values (middle) and monthly averaged values (bottom) are considered.

1. daily values;
2. daily values averaged for ten days;
3. daily values averaged for a month.

The fitting curves for the Ångström-Prescott, the Hardgreaves-Samani and the two Dumas relations were simply be obtained by least square methods. On the contrary, for the Bristow-Campbell equation, which cannot be linearized, we used some variants of the Levenberg-Marquardt algorithm in order to determine the parameters $a$, $b$ and $c$ in (3) for the regression curve.
In the following we'll first treat separately the two Dumas equations, and then we'll expose the comparison between the various solar energy models.

### 4.1. The two Dumas equations

In Figures 5, 6 we report the dispersion graphs of the couples $(G, F)$ and $(N, F)$ for the site of Manfredonia and Portici, together with their regression lines. Both the daily values and the averaged ones are considered. As we can see, all the couples of variable are well correlated, even if the correlation coeffiicent $r$ is higher for $(G, F)$, in both cases. Data from Manfredonia's site match better, as it was expected from Fig. 3. In Tables 1 and 2 we report the values of the coeffcients $a$ and $b$ relative to eq. (4) and eq. (6), together with the correlation coefficient $r$ and the root mean square error $RMSE$, which we remember is defined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}}$$

Here $d_i$ is the difference between the measured value with the estimated one, while $n$ is the number of measures.

About the models' responses at varying collecting data, we note that in the case of Manfredonia the coefficient $b$ is almost constant in both the first and the second Dumas equation, while the coefficient $a$ is subject to some variations.

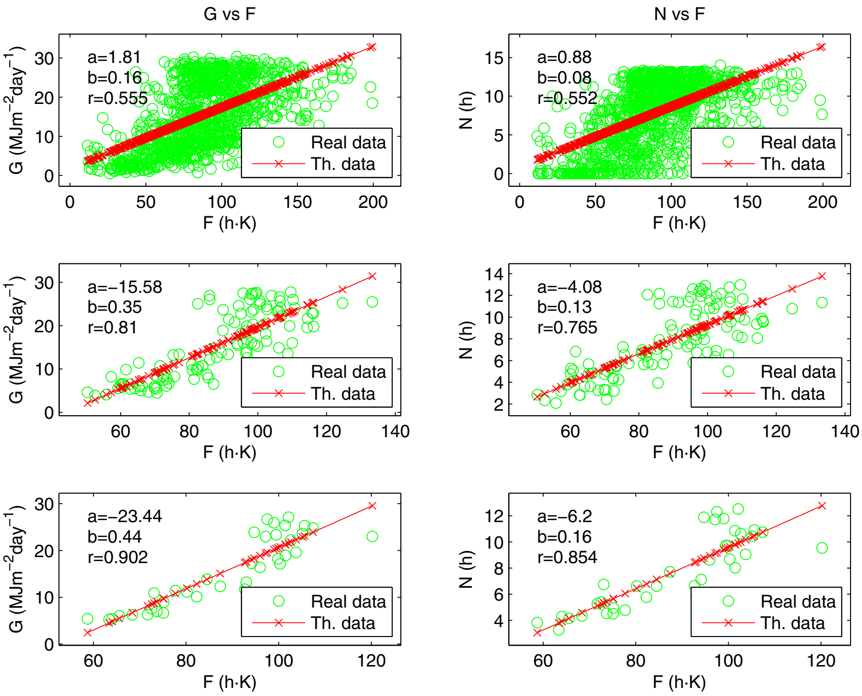


Fig. 3. $(G, F)$ and $(N, F)$ dispersion graphs for Portici's site. Daily values (top), ten days averaged values (middle) and monthly averaged values (bottom) are considered.

Table 1. Various parameters relative to the first and second Dumas equations for the site of Manfredonia. *d* = daily values, *td* = ten days averaged values, *m* = monthly averaged values.

| Equation | Type of data | *a* | *b* | *r* | *RMSE* |
|---|---|---|---|---|---|
| First Dumas eq. | *d* | −1.67 | 0.14 | 0.884 | $4\ MJm^{-2}d^{-1}$ |
| | *td* | −4.91 | 0.16 | 0.974 | $1.75\ MJm^{-2}d^{-1}$ |
| | *m* | −5.19 | 0.16 | 0.99 | $1.05\ MJm^{-2}d^{-1}$ |
| Second Dumas eq. | *d* | −0.05 | 0.06 | 0.794 | 2.67 *h* |
| | *td* | −0.17 | 0.06 | 0.927 | 1.2 *h* |
| | *m* | −0.02 | 0.06 | 0.97 | 0.71 *h* |

For Portici, the parameter *b* tends to vary too. From the values of *r* and *RMSE* we deduce that the overall performance of the models increases from daily values to monthly averaged ones.

### *4.2. Comparison between solar energy models*

For this task, the data of Manfredonia and Portici have been applied to the Ångström-Prescott, the Hardgreaves-Samani and the Bristow-Campbell models, besides the Dumas one. The relative dispersion graphs with their best fitting curves are shown in Figure 4 for Manfredonia and Figure 5 for Portici (only the monthly averaged values are shown).

For what concerns Manfredonia, the results show a good correlation for all the models. The Dumas equation is

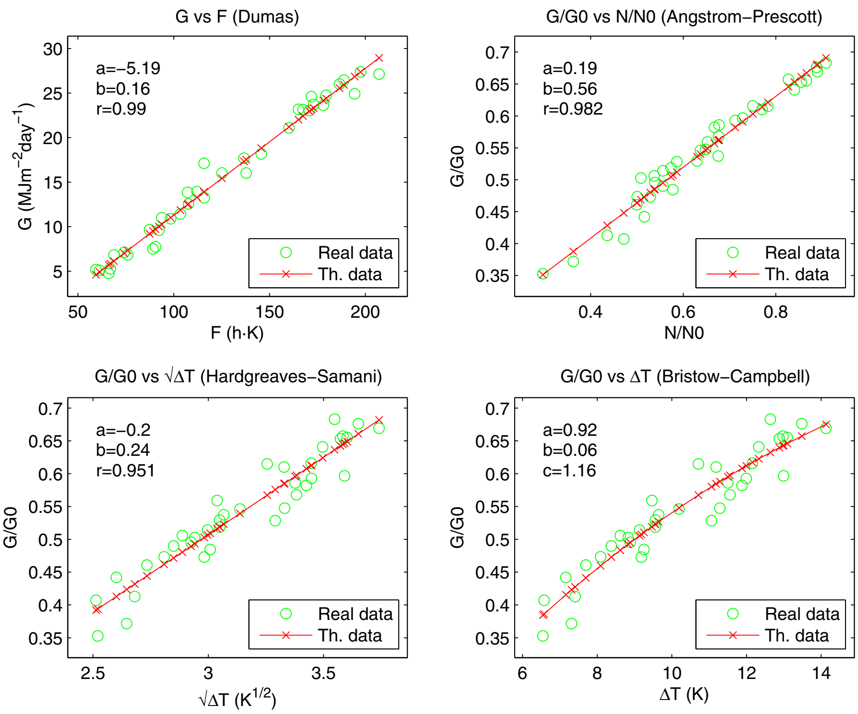


Fig. 4. Comparison among the Dumas relation with other empirical relations usually used in estimating $G$ for the sites of Manfredonia. Data refer to monthly averaged values for the years 2007 – 2009.

Table 2. Various parameters relative to the first and second Dumas equations for the site of Portici. $d$ = daily values, $td$ = ten days averaged values, $m$ = monthly averaged values.

| Equation | Type of data | $a$ | $b$ | $r$ | $RMSE$ |
|---|---|---|---|---|---|
| First Dumas eq. | $d$ | 1.81 | 0.16 | 0.555 | 7.04 $MJm^{-2}d^{-1}$ |
| | $td$ | −15.58 | 0.35 | 0.81 | 4.48 $MJm^{-2}d^{-1}$ |
| | $m$ | −23.44 | 0.44 | 0.902 | 3.22 $MJm^{-2}d^{-1}$ |
| Second Dumas eq. | $d$ | −0.88 | 0.08 | 0.552 | 3.54 $h$ |
| | $td$ | −4.08 | 0.16 | 0.765 | 1.98 $h$ |
| | $m$ | −6.2 | 0.13 | 0.854 | 1.47 $h$ |

the best one, for montly averaged values; as reported in Table 3, its correlation coefficient is $r = 0.99$ against the value of $r = 0.982$ and $r = 0.971$ for the A-P and the H-S. On the contrary, the other parameter that we have chosen to quantify the goodness of the various models, the $RMSE$, gives different answer: it results that the A-P model guarantees the lowest value of $RMSE = 0.38 MJm^{-2}d^{-1}$, while the highest value $RMSE = 1.05 MJm^{-2}d^{-1}$ is obtained with the Dumas equation. For the other temperature based model we have almost the same value of $RMSE = 0.76 MJm^{-2}d^{-1}$. All the models seem to perform better if averaged values are considered, with the A-P which is less subject to variations for its correlation coefficient. For the A-P, the H-S and the B-C equations, all the parameters doesn't change significantly when we vary the type of data collections; as we have previously said, this is not true for the coefficient $b$ of the first Dumas equation.

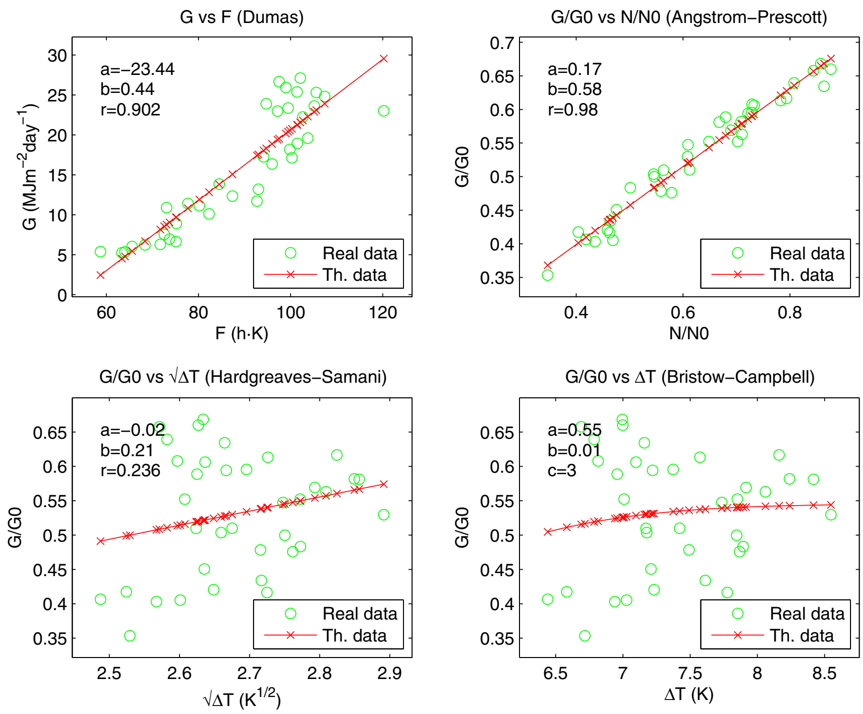


Fig. 5. Comparison among the Dumas relation with other empirical relations usually used in estimating $G$ for the sites of Portici. Data refer to monthly averaged values for the years 2007 – 2009.

For the site of Portici, the fitting's quality is generally lower, with the exception of A-P. Actually the Dumas equation still works well, at least for ten days and monthly averaged data for which $r = 0.81$ and $r = 0.9$. On the contrary, for H-S the parameter $r$ drastically decrease below 0.5, while for B-C, about which we don't dispose of an adeguate parameter of correlation since it is non linear, a look at the scatter plots in Figure 5 actually reveals the same caotic and randomly distribution of its variables as H-S.
However, even in this situation, the *RMSE* values for the H-S and B-C models are little below those of the Dumas equation, as we can see in Table 4, both for daily and averaged data, which means in some way the H-S and the B-C curves fit the data better then the Dumas relation, despite of this wide difference in correlation. Even for Portici, the coefficient of the A-P, the H-S and the B-C equations doesn't vary appreciably for different data collections, with the exception of the parameter $c$ in (3); besides, they are not so much different then the analogous parameters for Manfredonia site; in some sense, we can say that A-P, H-S, and B-C are most stable then the first Dumas equation. While all the models improve their *RMSE* by passing from the daily values to the monthly averaged ones, the correlation coefficient of H-S decreases.

## 5. Conclusion

The analysis of the sites of Manfredonia and Portici allows tracing various conclusions and emerging of some open questions. Even if the number of sites and the number of years considered in the paper is too low to furnish wide experimental evidences, this study evidences that the Dumas method produces a good description of the solar irradiation and the sunshine duration, independently of the particular site chosen at least if averaged values of $G$, $N$ and $\Delta T$ are taken. If compared other models, it presents values of *RMSE* are a bit higher not just with respect to the Ångström-Prescott relation but also to the Hardgreaves-Samani and the Bristow-Campbell ones. However, even if the Hardgreaves-Samani and the Bristow-Campbell models are slightly better in *fitting* the present data, in *predicting* the data – i.e. in estimating the future values of $G$ from those of $\Delta T$ with the parameters fixed from the history data –

Table 3. Table of comparison between the first Dumas equation and the Ångström-Prescott, Hardgreaves-Samani and Bristow-Campbell equations for the site of Manfredonia. *d* = daily values, *td* = ten days averaged values, *m* = monthly averaged values.

| Equation | Type of data | $a$ | $b$ | $c$ | $r$ | $RMSE$ $(MJm^{-2}d^{-1})$ |
|---|---|---|---|---|---|---|
| First Dumas eq. | *d* | −1.67 | 0.14 | – | 0.884 | 4.004 |
| | *td* | −4.91 | 0.16 | – | 0.974 | 1.757 |
| | *m* | −5.19 | 0.16 | – | 0.99 | 1.05 |
| Ångström-Prescott eq. | *d* | 0.21 | 0.53 | – | 0.96 | 1.342 |
| | *td* | 0.19 | 0.54 | – | 0.98 | 0.493 |
| | *m* | 0.19 | 0.56 | – | 0.982 | 0.375 |
| Hardgreaves-Samani eq. | *d* | −0.2 | 0.24 | – | 0.749 | 3.146 |
| | *td* | −0.23 | 0.25 | – | 0.888 | 1.423 |
| | *m* | −0.2 | 0.26 | – | 0.951 | 0.756 |
| Bristow-Campbell eq. | *d* | 0.7 | 0.03 | 1.77 | – | 2.996 |
| | *td* | 0.78 | 0.04 | 1.44 | – | 1.432 |
| | *m* | 0.9 | 0.06 | 1.18 | – | 0.764 |

Table 4. Table of comparison between the first Dumas equation and the Ångström-Prescott, Hardgreaves-Samani and Bristow-Campbell equations for the site of Portici. *d* = daily values, *td* = ten days averaged values, *m* = monthly averaged values.

| Equation | Type of data | $a$ | $b$ | $c$ | $r$ | $RMSE$ $(MJm^{-2}d^{-1})$ |
|---|---|---|---|---|---|---|
| First Dumas eq. | *d* | 1.81 | 0.16 | – | 0.55 | 7.04 |
| | *td* | −15.58 | 0.35 | – | 0.81 | 4.4 |
| | *m* | −23.44 | 0.44 | – | 0.90 | 3.21 |
| Ångström-Prescott eq. | *d* | 0.2 | 0.53 | – | 0.97 | 1.16 |
| | *td* | 0.18 | 0.56 | – | 0.98 | 0.5 |
| | *m* | 0.17 | 0.58 | – | 0.98 | 0.45 |
| Hardgreaves-Samani eq. | *d* | 0.07 | 0.17 | – | 0.43 | 4.14 |
| | *td* | 0 | 0.2 | – | 0.33 | 2.42 |
| | *m* | −0.02 | 0.21 | – | 0.24 | 2 |
| Bristow-Campbell eq. | *d* | 0.6 | 0.09 | 1.7 | – | 3.98 |
| | *td* | 0.57 | 0.04 | 2.17 | – | 2.17 |
| | *m* | 0.55 | 0.01 | 3 | – | 1.99 |

the present values of the correlation coefficients highly suggest that the Dumas equation could be the best choice, in particular for sites with low daily temperature variation.
To produce a more complete evaluation it is necessary to increase the number of tested sites number of sites and in particular to increase the time-frame in order to produce a more accurate comparison of the models with particular

respect to their capability of prediction. This future activity could produce an effective answer to the open questions that promising research activity has raised from its preliminary stage.

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