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Estimation of total atmospheric pollution using global radiation data: introduction of a novel clear day selection methodology

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Abstract

This work investigates the possibility of determining the degree of atmospheric pollution over the small Greek city of Serres based solely on measurements of global solar radiation and some simple meteorological variables. Hourly data of solar irradiance on an horizontal plane are recorded simultaneously together with relative humidity and wind speed. Along with some traditional techniques for selecting the clear sky days of the period examined, the statistical coefficients of skewness and kurtosis of the daily distributions of hourly radiation data have been employed with reasonable success. Indeed, for the cloudless days of this study, the values of the above quantities are confined within narrow ranges which provide a criterion for their identification from the cloudy days. Comparison of global radiation data under clear sky conditions with reference values from a suitable theoretical model of literature, in combination with the results of a recent study for the nearby city of Thessaloniki, provides evidence that there is virtually no atmospheric pollution in Serres. Correlation of the observed deviations between measurements and predictions with recorded meteorological data lends further support to the above argument. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Global radiation; Atmospheric pollution; Relative humidity; Wind speed; Skewness; Kurtosis; Statistical moments

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1. Introduction

Solar radiation as it passes through the atmosphere undergoes absorption and scattering by various constituents of the atmosphere. The amount of solar radiation finally reaching the surface of earth depends quite significantly on the concentration of airborne particulate matter, gaseous pollutants and water (vapor, liquid or solid) in the sky, which can further attenuate the solar energy and change the diffuse vs direct radiation ratio [1]. Over industrial and densely inhabited areas atmospheric pollution is greater than elsewhere because the presence of aerosol particles and other pollutant materials in these areas is intense. One way of estimating the atmospheric pollution in such places, at least preliminarily, is by measuring the local availability of solar energy, preferably the direct radiation component. Unfortunately, measurements of direct solar radiation are still not available for many locations. On the contrary, measurements of global (direct + diffuse) solar radiation are more common [2, 3]. Utilizing global radiation measurements for a reliable estimation of the atmospheric condition represents a very tempting option, given the simplicity and the low equipment/maintenance costs involved.

Several studies have been conducted for Athens and Thessaloniki, two highly populated Greek cities with prominent air pollution problems, to characterize their atmospheric status incorporating solar radiation measurements [4–8]. Some of these studies have analysed direct solar radiation data and calculated several atmospheric turbidity coefficients in order to examine the atmospheric quality. Sahsamanoglou et al. [8] communicated a study for Thessaloniki (latitude 40°33′, longitude 23°01′, altitude 30 m) where the atmospheric pollution was estimated by comparing recorded values of global radiation under cloudless sky with values predicted by a suitable empirical model of literature [9]. This was done in the absence of appropriate (pollution-free) reference measurements outside the city. The model by Heermann et al. [9] was developed from data collected at several locations in U.S.A. with latitude similar to that of Thessaloniki. Simple equations were derived to estimate daily clear sky global radiation using solar elevation (calendar date), latitude and altitude as the principal variables. As a matter of fact, comparisons between experimental data and model predictions for different sites around the globe are frequently non-realistic because local and regional climatological and meteorological conditions can have a dramatic effect on both the availability and the spectral distribution of solar radiation [10, 11]. In effect, regarding solar radiation measurements, the only evidence of atmospheric pollution beyond all reasonable doubt, can originate from comparisons with experimental reference (pollution-free) data which however are rather scarce.

The present study reports global horizontal irradiation data collected in the city of Serres (latitude 41°07′, longitude 23°34′, altitude 32 m), the capital of a large rural prefecture with approximately 200,000 inhabitants. The city itself has less than 70,000 inhabitants. Data are integrated over 1 h intervals, for the period between 10 May 1995 and 9 May 1996 with an Eppley Precision Pyranometer (model PSP), which was calibrated at the beginning of the measuring period. The estimated overall error in solar irradiance measurements—including calibration, measurement, digitization and data handling—is always less than 3%. Global solar radiation is measured simultaneously with relative humidity, wind speed, wind direction and ambient temperature but only the first two variables are utilized in the present study.

This work is part of an effort to register the environmental conditions in the prefecture of Serres. An additional motivation for this particular report is to compare the results of this study to that of Sahsamanoglou et al. [8] for Thessaloniki. Serres is a small city near Thessaloniki having similar meteo-climatic conditions. It is the social and commercial center of the prefecture with a moderate number of vehicles and a limited industrial activity. Whether these features are responsible for a rather expected clean atmosphere over the city is under current investigation. On this account, it is useful to compare global radiation data collected in Serres under clear sky conditions with pollution-free reference values. Additionally, it is of particular interest to explore the effects of weather variables on the local availability of global solar irradiance. To the best of the authors' knowledge, such effects have received relatively little attention in the region of Greece and only for the cases of the two large cities, Athens and Thessaloniki [6, 7]. Finally, a novel statistical methodology is examined, capable of minimizing the logistics in the identification of the clear sky days among the days of a prolonged period of time.

2. Data analysis

2.1. Average radiation data

Monthly average values of hourly global radiation data are found to agree reasonably well with the predictions given by ELOT [12]—the Greek Bureau of Standards—for Serres [13]. Despite the short measuring period examined, it has been seen that the annual deviation from ELOT [12] is only $\sim 3\%$ whereas the monthly average values are scattered in the range $\pm 20\%$, a substantial variation that must be taken into account when designing solar energy systems. Considering the above, it seems that the new data presented herein are accurate and evidently representative of the solar radiation climatology of Serres.

2.2. Identification of clear sky days

Several reports have used the clearness index, K_t, defined as the ratio of earth's surface global to extraterrestrial radiation, to characterize insolation conditions and therefore describe atmospheric conditions [14–16]. Daily K_t-values larger than a critical value, e.g. 0.60 or 0.64, are tacitly considered to reflect cloudless or nearly cloudless conditions. However, the same critical value has not been used in all studies. Besides, partly cloudiness can not be described by either daily or sometimes even hourly clearness index data [2, 3]. By applying the constraints of $K_t > 0.60$ and $K_t > 0.64$ to the data of this work, 146 and 107 days, respectively, are selected representing cloudless conditions (39.9% and 29.2% of the period examined). These numbers are much higher than the values communicated for other regional sites, e.g. Thessaloniki, 21.3% [8]; Istanbul, 24% [16]. Careful inspection of the hourly radiation measurements for every single day of the period examined reveals that none of the above constraints is capable by itself of identifying the actual clear sky days.

A visual scrutiny of the experimental daily radiation curves is employed next, to select clear sky days whenever cloudiness does not obscure the sightpath. This technique is a common practice in this type of research [6, 8]. The clear sky days isolated by visual screening in this work are 86, 23.5% of the period examined. Alternatively, by plotting observed daily radiation values for the period examined and determining an envelope curve through high points, a similar estimation of cloudless day solar radiation values is obtained. However, the traditional visual screening of daily radiation curves, albeit very meticulous, is extremely cumbersome if one has to cope with data from a prolonged period of time. Therefore, attention is focused next on the possibility to determine rigorous statistical criteria, based solely on global radiation data, for isolating the clear sky days.

As already observed by previous investigators, daily distributions of hourly global radiation measurements are often asymmetric due to partial cloudiness or intermittent cover of optically dense clouds or haze. An often used statistical measure of asymmetry, is the coefficient of *skewness* (α_3), defined by means of the third and second central moments of the data [17].

$$\alpha_3 = m_3/(m_2)^{3/2} \tag{1}$$

For perfectly symmetrical distributions α_3 becomes zero. Evidently, skewness is not capable to differentiate between actual clear sky days and overcast days with homogeneous cover of clouds or cirrus throughout. Thus, the term *kurtosis* is usually employed to express the degree of 'peakedness' or 'flatness' of a distribution, taken relative to a normal distribution. The measure of kurtosis used here is the coefficient of kurtosis (α_4), based on the normalized fourth central moment of the data [17].

$$\alpha_4 = m_4/m_2^{\ 2} \tag{2}$$

For a normal distribution α_4 is equal to three. The aforementioned high-order statistical moments have been successfully employed in the past to study spatio–temporal structures in several fields of environmental research, i.e. wind-induced sea waves [18], free falling films [19], free jet turbulence [20], environmental control [21].

Daily coefficients of skewness (α_3) and kurtosis (α_4) are calculated for all the hourly radiation data collected in this study, taking the discrete hour-values of the day as the variable, whereas the hourly radiation data are utilized as their corresponding probability density values, otherwise referred to as frequency of occurrences. The justification for doing this comes from extensive simulation tests we performed to the hourly radiation data for Serres—predicted by the model of Lalas et al. [22]—and is as follows. Hourly irradiance values plotted against hours of the day produce curves that, for clear sky conditions, are symmetrical around a mean value ($\alpha_3 = 0$) regardless the calendar date. As for the kurtosis of these curves, it is seen that the effect of the increased irradiance level in summertime is sufficiently counterbalanced by a respective increase in sunshine duration, with the ultimate effect of virtually the same kurtosis value all over the year. A summary of this analysis is presented in Table 1.

Table 1
Coefficients of skewness (α_3) and kurtosis (α_4) calculated from simulated monthly average daily radiation data for Serres by Lalas et al. [22]

Month	Skewness	Kurtosis
January	0.08	2.31
February	0.01	2.29
March	0.03	2.21
April	0.05	2.25
May	0.01	2.27
June	0.03	2.26
July	0.02	2.24
August	0.02	2.18
September	0.04	2.24
October	0.01	2.25
November	0.09	2.21
December	0.00	2.20
Year		
Average	0.03	2.24
SD	0.03	0.04
Maximum	0.09	2.31
Minimum	0.00	2.18

Values of the coefficients of skewness (α_3) and kurtosis (α_4) calculated as outlined above, are displayed in Fig. 1. It is clearly seen that for the visually screened cloudless days both quantities remain essentially constant throughout the year. Table 2 presents some additional information about the variation of the two moment coefficients. For these clear sky days, the skewness (α_3) varies from practically 0–0.09 whereas the coefficient of kurtosis (α_4) from 2.18–2.33. As can be seen, there is a reasonable accord with the predicted average values for Serres in Table 1.

Applying the above criteria to the hourly data of this study, 36% of the examined days are identified as cloudless, instead of the 23.5% visually determined. Evidently, some cloudy days also satisfy the inclusion criteria. For hourly data, which nowadays represent the majority of the measurements around the globe, one way to partly overcome this difficulty is by requiring the daily average clearness index, K_t, of the statistically selected cloudless days to be above a certain value. After data assessment, it was decided that for this purpose a conservative clearness index value, which does not warrant further consideration, is 0.60. By applying the constraint $K_t > 0.60$ to the statistically selected days, 30% of the days are still identified as cloudless which corresponds to just 9% of the actually cloudy days remaining undesignated. This 9% appears to be a lower bound for the hourly radiation data of this study. Whether these skewness (α_3), kurtosis (α_4) and clearness index (K_t) values represent ranges of general validity for sorting out hourly measurements, should be tested further with time records of size larger than that employed here and from different sites.

Some insight into the role played by the location of a site is gained from Table 3

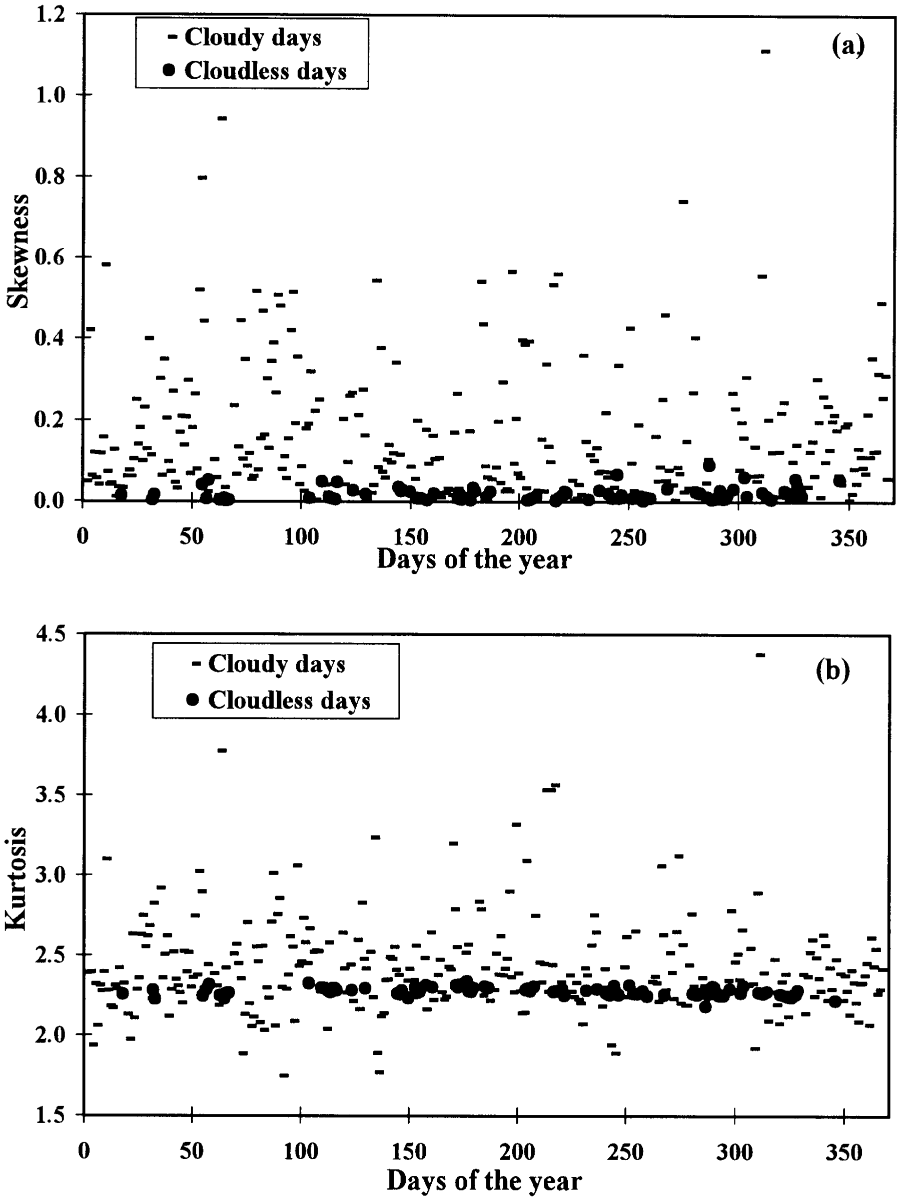

Fig. 1. Daily coefficients of skewness (α_3) and kurtosis (α_4) calculated with the hour-values of the day as the variable, utilizing the hourly radiation data as the respective frequency of occurrences.

where the present analysis is applied to one-year-round data from 10 different sites across U.S.A. [23]. Although the selection of these data is arbitrary, an effort is made to sufficiently span them in both space (site) and time (year). For the statistically

Table 2
Characteristic statistical values of the coefficients of skewness (α_3) and kurtosis (α_4) calculated for both cloudless and cloudy days

	Cloudless days		Cloudy days	
	Skewness	Kurtosis	Skewness	Kurtosis
Average	0.02	2.27	0.16	2.43
SD	0.02	0.03	0.16	0.31
Maximum	0.09	2.33	1.11	4.38
Minimum	0.00	2.18	0.00	1.75

Table 3
Percentage of identified clear sky days for different sites. Selection is based either solely on the criteria of skewness (α_3) and kurtosis (α_4) or together with the constraint for the daily average clearness index, $K_t > 0.60$

Site	Year	%, (α_3, α_4)	%, (α_3, α_4, K_t)
Serres, Gr	1995/96	36	30
Austin, TX	1980	52	41
Long Beach, CA	1990	50	42
Atlanta, GA	1990	48	39
Honolulu, HI	1985	44	30
Eagle, CO	1977	41	28
Boston, MA	1980	40	29
Detroit, MI	1985	40	22
Philadelphia, PE	1977	38	26
Portland, OR	1977	25	12
Seattle, WA	1980	23	10

selected clear sky days, it seems that sites with either similar latitudes or from the same region, group together at similar percentages. This result is most expected since, for instance, sites in the south (Austin, Long Beach, Atlanta, U.S.A.) experience many more cloudless days per year than sites on the frequently overcast north Pacific coast (Portland, Seattle, U.S.A.). On the other hand, for sites in the mid-land (Detroit, Eagle, U.S.A.) and on the Atlantic coast (Boston, Philadelphia, U.S.A.) with latitudes not largely different from Serres, the identified number of clear sky days are very much alike to each other and to Serres. Of course, any systematic behavior should be investigated further over a broader range of conditions.

By inspecting the radiation curves of those cloudy days that have coefficients values similar to actual clear sky days and are, therefore, misclassified as such, one can see

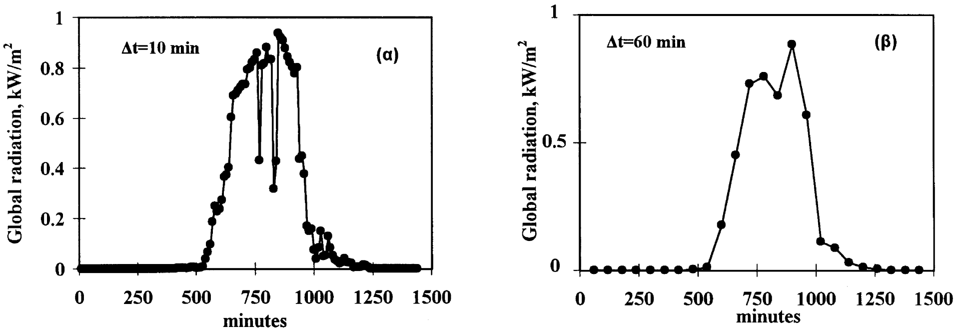

Fig. 2. Typical daily radiation curves with partial cloudiness occurrence, (a) integration interval $\Delta t = 10$ min; (b) integration interval $\Delta t = 60$ min.

that most of them are characterized by an almost symmetrically distributed daily irradiance with just a single-point weak disturbance due to partial cloudiness. The problem is particularly acute in days that have a small number of non-zero hourly radiation measurements, e.g. in winter, where the capacity of the calculations is diminished. Obviously, the temporal resolution of the measurements ($\Delta t = 1$ h) does not permit a very accurate depiction of daily irradiance curves, which results in fluctuations of the calculated coefficients values. This is also seen in the calculations of the simulated hourly data of Table 1. As a matter of fact, shorter integration intervals ($\Delta t = 10$–30 min) incorporated during exploratory preliminary measurements in our lab improved noticeably the overall performance, indicating clearly that the coefficients of skewness and kurtosis can offer a sufficiently stringent criterion for isolating clear sky days. This is easily observed in the calculations for a typical radiation curve, e.g. as in Fig. 2, where partial cloudiness gives spurious results at longer integration intervals, Table 4.

In conclusion, the analysis presented here offers a convenient and time-saving preliminary screening tool for the manipulation of hourly data, even more so if one notes that it does not require fine adjustment of the time records to true sun time.

Table 4
Coefficients of skewness (α_3) and kurtosis (α_4) calculated for various integration intervals for a typical daily radiation curve

Integr. interval Δt, min	Skewness α_3	Kurtosis α_4
10	0.188	2.806
20	0.190	2.803
30	0.185	2.817
40	0.160	2.788
50	0.194	2.821
60	0.158	2.798

2.3. Estimation of atmospheric pollution

A way to check the possibility of atmospheric pollution in the city of Serres is by comparing measured daily global radiation data under clear sky conditions, with experimental reference (pollution-free) local values. A combined procedure, with the statistical screening preceding the tedious visual one, has been employed in the present study for the isolation of the cloudless days. This new statistical procedure does not affect the original visual selection but only speeds it up. Due to the paucity of experimental reference data obtained outside Serres, the model predictions of Heermann et al. [9] are employed in pursuing the comparisons, which are claimed to describe satisfactorily the regional clear sky insolation conditions [8].

The model equation by Heermann et al. [9] is

$$R = A + B \times \cos(2\pi d/365 - C) \tag{3}$$

where:
R: is the estimated solar radiation on a clear day d, [MJ/m^2]
A: the mean daily solar radiation, [MJ/m^2]
B: the amplitude of the daily values, [MJ/m^2]
C: the phase constant which is set theoretically at a value corresponding to the longest day of the year (i.e. day 172 or 21st of June).

Empirical coefficients A and B are functions solely of latitude (l) and altitude (h) of the site (for Serres $l = 41°07'$ and $h = 32$ m) and they are determined by

$$A = 31.54 - 0.2734^{*}\, l + 0.0007813^{*}\, h \tag{4}$$

$$B = -0.2986 + 0.2678^{*}\, l + 0.0004102^{*}\, h \tag{5}$$

Figure 3 shows the comparison between measurements and model predictions for the visually screened cloudless days in Serres. Daily deviations are between $\sim +3\%$ and $\sim -17\%$ whereas the annual mean deviation is less than -8%. Such differences are close to the order of accuracy of the model ($\pm 5\%$) and the estimated experimental error ($\pm 3\%$) and indicate that there is rather no atmospheric pollution in Serres. It must be recalled here that for Thessaloniki the observed daily global radiation values of visually screened clear sky days when compared to the predictions of the same model were *always* less, in the range from -15% to -50% [8]. This difference was attributed to a prominent air pollution background over the city of Thessaloniki.

In principle, the possibility can not be excluded that deviations larger than $\sim 8\%$ in Fig. 3, may be due to some air pollution in the atmosphere of Serres. In order to allow speculation about the origin of such deviations, Fig. 4(a,b) displays the percentage differences of clear sky global radiation from the model predictions (eqn 3–5) against the weighted, with respect to hourly global radiation, relative humidity and wind speed. Discrepancies between data and predictions increase with relative humidity and decrease with wind speed. As shown elsewhere [13], high humidity and low wind speed conditions regularly characterize south–southwest (S–SW) winds in Serres. In view of the geomorphology of the city, which is surrounded by a low mountain complex in the N–NE and widespread flat fields in the S–SW, it is felt that

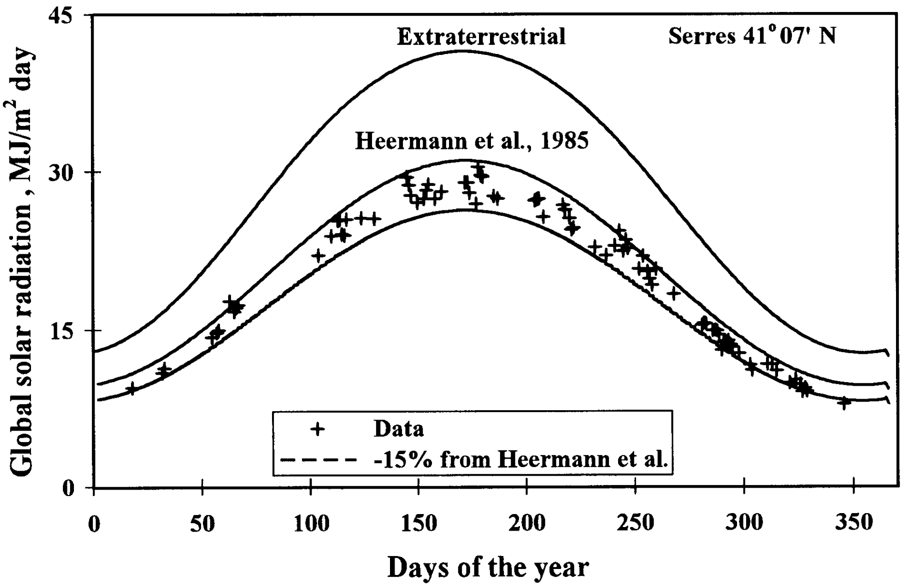

Fig. 3. Comparison of daily values of global radiation data under cloudless conditions with the predictions by the model of Heermann et al. [9].

the largest deviations displayed in Fig. 3 can be attributed, at least in part, to the moderate S–SW winds blowing in the area. These winds are capable of carrying substantial quantities of vapors and minute airborne particles from the adjacent rural fields, irrigation open channels and nearby rivers of Belitsa and Strimonas. Evidently, more work is required to clarify this issue.

In addition, it has been also reported for Serres [13] that during cloudless days, winds with a speed just above ~ 3 m/s are always accompanied by increased radiation levels. This can be the case only for a rather clean atmosphere whilst for more loaded ones, e.g. for Thessaloniki, much stronger winds are required [7]. This argument, apparently, lends further support to the notion that the atmosphere of Serres is pollutant free.

To this end, it appears that the model equations by Heermann et al. [9] can be used for this region of Greece with considerable success. Radiation data from the rather clean atmosphere of Serres may be considered quite suitable to test the model predictions in the region. Moreover, the present data for Serres support further the conclusions for Thessaloniki. Of course, measurements over a longer period of time are required before definitive statements can be made.

3. Conclusions

The present study provides new evidence regarding the utilization of global solar radiation measurements for the reliable estimation of atmospheric pollution. First, a

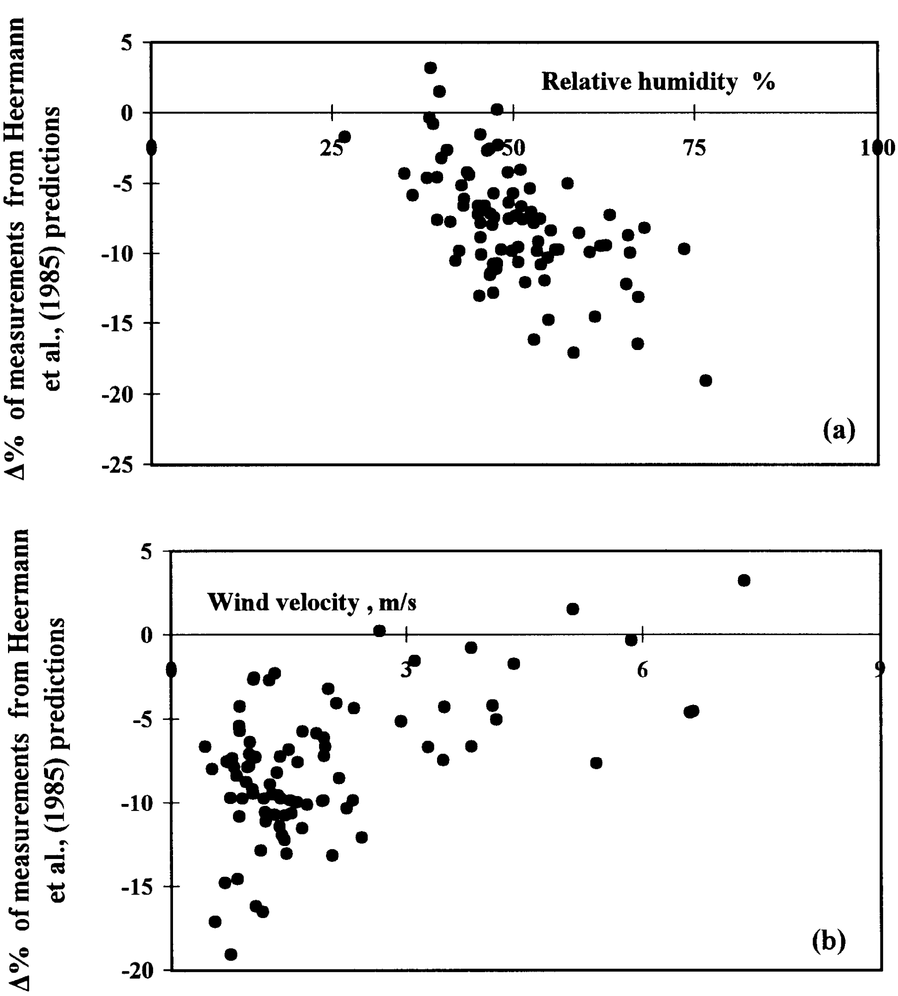

Fig. 4. Percentage deviations of measured global radiation data for clear sky days from the model predictions by Heermann et al. [9] vs (a) relative humidity and (b) wind speed.

combination of the coefficients of skewness and kurtosis of the daily distributions of hourly radiation data is proposed as a quite sensitive criterion for isolating cloudless days. For the clear sky days of this study, the values of the aforementioned coefficients fall within somewhat narrow ranges which permit their prompt identification from the majority of the cloudy days. These statistical quantities seem to offer apparent advantages over traditional methods for identifying clear sky days as regards convenience and labor. Nevertheless, one should withhold judgment on their merit until questions relating to the period of data acquisition and to integration intervals are resolved. Work in that direction is under way.

For clear sky days, the measured global radiation data collected in Serres agree reasonably well with the corresponding predictions of the empirical model by Heermann et al. [9]. For the nearby city of Thessaloniki, a discrepancy from −15% to −50% was observed between data and predictions throughout the year, a fact which was attributed to the existence of air pollution in the city [8]. These observations combined, imply that Serres has an essentially clean atmosphere while the conclusions for Thessaloniki are further supported. Moreover, it seems that the model of Heermann et al. [9] can be applied for this region of Greece with considerable success. Cross examination of the measured solar radiation data with synchronously recorded weather variables such as, relative humidity and wind speed reinforces our confidence in the conclusion of a pollution-free atmosphere over Serres.

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