Comparison of Pyranometric and Pyrheliometric Methods for the Determination of Sunshine Duration

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ABSTRACT

Two pyranometric methods for the determination of sunshine duration (SD) from global irradiance measurements are evaluated by means of summated sunshine seconds derived from pyrheliometric measurements in combination with the WMO threshold of 120 W m^{-2} for the direct solar irradiance. The evaluation is performed using direct and global radiation measurements made at the Cabauw Baseline Surface Radiation Network (BSRN) site in the Netherlands for the period March 2005–February 2006. The "Slob algorithm" uses 10-min mean and extreme values of the measured global irradiance and parameterized estimates of the direct and diffuse irradiance. The "correlation algorithm" directly relates SD to 10-min mean measurements of global irradiance. The cumulative pyrheliometric SD for the mentioned period is 1429 h. Relative to this value, the Slob algorithm and correlation algorithm give −72 h (−5%) and +8 h (+0.6%). On a daily mean basis, the values are -0.22 ± 0.05 h day^{-1} and 0.03 ± 0.03 h day^{-1}, respectively. By means of tuning the irradiance parameterizations of the Slob algorithm, the yearly cumulative and daily mean differences can be reduced to +7 h (+0.5%) and 0.02 ± 0.04 h day^{-1}, respectively. It is concluded that, by use of either algorithm, it is possible to estimate daily sums of SD from 10-min mean measurements of global irradiance with a typical uncertainty of 0.5–0.7 h day^{-1}. For yearly sums, the uncertainty typically amounts to 0.5%.

1. Introduction

Sunshine duration measurements have been made at many locations around the world for over a century, using different methods and instruments. In De Bilt, Netherlands, for example, sunshine duration has been measured since 1901 by the Royal Netherlands Meteorological Institute (KNMI) (Heijboer and Nellestijn 2002). Since long time series of sunshine duration measurements exist, they have a climatological and historical value and time-dependent variations can be studied, as was done, for example, for the United States (Angell and Korshover 1975, 1978; Winston 1976; Angell 1990; Stanhill and Cohen 2005), for China (Kaiser and Qian 2002), for Ireland (Pallé and Butler 2002), for Germany (Power 2003), for Turkey (Aksoy 1999), and for tropical climates (Tiba and Fraidenraich 2004). Sunshine duration can be used to characterize the climate of a particular region and is used in, for example, tourism. Furthermore, if solar radiation measurements are not available, sunshine duration data can be used as a proxy for the solar irradiance, which is a valuable quantity for agriculture, architects, and various solar energy applications (Velds 1992).

An example of a climatological map of sunshine duration is shown in Fig. 1, which shows the distribution of yearly sunshine duration for the Netherlands, averaged over the period 1971–2000. The figure shows a distinct longitudinal gradient with most sunshine hours near the coast. This is caused by a west–east increase in cloud cover, which in turn is caused by dominating westerly winds that advect moist air from sea to the relatively convective atmosphere over land. The relation between cloudiness and sunshine duration has been studied by, for example, Stanghellini (1981), Essa and Etman (2004), and Rahim et al. (2004).

A commonly used instrument for the measurement of sunshine duration is the Campbell–Stokes sunshine

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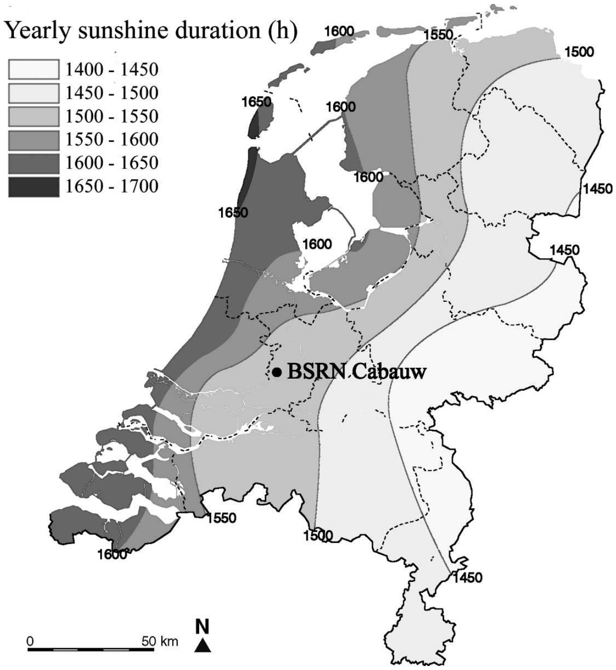

FIG. 1. Distribution of yearly sunshine duration (h yr^{-1}) for the Netherlands, averaged over the period 1971–2000 (Heijboer and Nellestijn 2002). Until 1 Oct 1992 sunshine duration has been determined by means of the Campbell–Stokes sunshine recorder at about 25 stations. From that date onward, sunshine duration has been estimated from global irradiance according to an adjusted version of the Slob algorithm (see sections 2 and 5). The BSRN site of Cabauw is indicated. The analysis presented here is based on measurements of direct and global irradiance made at this site.

recorder (Coulson 1975, chapter 8). The instrument, which was already introduced in 1880, detects sunshine if the beam of solar radiation concentrated by a glass sphere burns a trace on a graduated paper card (WMO 2006). Nowadays, more sophisticated instruments are available that all rely on the formal definition of sunshine duration given by the World Meteorological Organization (WMO) in 1989: "sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W m^{-2}" (WMO 2006). For the detection of the threshold solar irradiance WMO recommends the use of a pyrheliometer mounted on a sun tracker system. For financial and maintenance reasons, the spatial distribution of pyrheliometric measurements, in for example national meteorological networks, is generally not dense. Global radiation, however, consisting of both direct solar and diffuse sky radiation, is often measured in dense networks of meteorological observations. To construct spatial distributions of sunshine duration over the Netherlands (Fig. 1), Slob and Monna (1991) developed an algorithm based on the WMO definition to estimate sunshine duration from global irradiance measurements made with pyranometers at about 30 stations operated by KNMI.

The reverse relation, that is, from sunshine duration to global radiation, has been studied extensively, for example for the Netherlands by Frantzen and Raaff (1982), but also for other parts of the world (see, e.g., Ångström 1924; Iqbal 1983; Gopinathan 1988; Al-Sadah and Ragab 1991; Hussain et al. 1999; El-Metwally 2005). These studies have been performed because in many countries sunshine duration is measured at more locations than global radiation, whereas knowledge of global radiation is desired for the design of systems that use solar energy. In most of these studies, daily cumulative values of sunshine duration are used. The algorithm designed by Slob and Monna (1991), however, is based on the use of mean, minimum, and maximum values of the measured global irradiance over a 10-min interval to estimate the sunshine duration for this interval. The algorithm relies on parameterized estimates of the direct and diffuse irradiance for cloudless conditions. Oliviéri (1998) also pointed out the possibility of using global irradiance for the estimation of sunshine duration. The method presented by this author is based on the assumption that a certain fraction (depending on day of year and time) of an empirical estimation of the global irradiance is only exceeded if the direct solar irradiance exceeds 120 W m^{-2}.

One of the objectives of the present paper is to evaluate the pyranometric method of Slob and Monna (1991) for the determination of sunshine duration. Furthermore, an alternative algorithm for the determination of sunshine duration, which directly relates sunshine duration to global radiation, will be presented. For these purposes, high-quality radiation measurements made at the Baseline Surface Radiation Network (BSRN; Ohmura et al. 1998) station in Cabauw, Netherlands (51.97°N, 4.92°E), are used (location indicated in Fig. 1). As far as known to the authors, this is the first peer-reviewed attempt to systematically compare pyranometric sunshine durations with those directly derived from the WMO definition. Previous studies involve, for example, an evaluation of a National Weather Service Foster sunshine recorder with sunshine durations derived from the WMO definition (Michalsky 1992) and a comparison between sunshine duration measurements from an optoelectronic sunshine duration sensor and the traditional Campbell–Stokes sunshine recorder (Mohnl and Koch 2006).

The organization of this paper is a follows. First, the pyrheliometric and pyranometric methods for the determination of sunshine duration are presented in section 2. In section 3, the solar radiation measurements made at the Cabauw BSRN site that were used for the analysis presented here are described. In section 4, sunshine durations as determined with the different methods are presented and compared. A discussion of the results is given in section 5. Conclusions are drawn in section 6.

2. Methods for the determination of sunshine duration

In this section the different methods for the determination of sunshine duration (SD) from direct irradiance measurements (pyrheliometric method) and global irradiance measurements (pyranometric method) are described. Two versions of the pyranometric method will be presented; the first is based on the algorithm developed by Slob and Monna (1991), and the second is based on an alternative algorithm that directly relates sunshine duration to global irradiance.

a. Pyrheliometric method

The pyrheliometric method is based on the WMO defintion of SD. WMO (2006) states that "the sunshine duration during a given period is defined as the sum of that subperiod for which the direct solar irradiance exceeds 120 W m^{-2}." The units used for SD are seconds or hours, but derived terms such as hours per day or season will also be used here. According to the WMO guide, hours of sunshine should be measured with an uncertainty of ±0.1 h and a resolution of 0.1 h. The analysis presented here is based on measurements of the direct solar irradiance (I) made at the Cabauw BSRN site in the Netherlands. According to the guidelines of BSRN, the target uncertainty for measurement of I is 0.5% or 1.5 W m^{-2} (McArthur 2005). Even if, in practice, the uncertainty could amount to a few watts per meter squared, we believe that the uncertainty in SD due to measurement uncertainty in I is well within the WMO recommended uncertainty of ±0.1 h. Since at Cabauw I is sampled with a frequency of 1 Hz, the pyrheliometric method gives *sunshine seconds*, which add up to, for example, minutes per 10-min interval or hours per day. Since the sampling time is less than the typical response time of a pyrheliometer (the 95% response time for the pyrheliometer used for present analysis is 7 s), no information is lost in the pyrheliometric direct irradiance signal. The use of sunshine seconds was earlier described by Forgan (2005), who assessed the uncertainty in daily sunshine duration from BSRN minute statistics for measurements made within the radiation network of the Australian Bureau of Meteorology.

b. Pyranometric methods

The first pyranometric algorithm that is discussed in the present subsection has been developed by Slob and Monna (1991). These authors aimed at obtaining realistic estimates of daily SD (h day^{-1}), using mean, minimum, and maximum values of measured global irradiance over 10-min intervals. In the rest of this paper the algorithm will be referred to as the Slob algorithm, named after W. H. Slob, a former KNMI employee who developed the algorithm using measurements of global, direct, and diffuse irradiance made in De Bilt, Netherlands, for the period 1986–89. The second algorithm presented here directly correlates the sunshine duration to 10-min mean measurements of the global irradiance and is mainly designed to obtain realistic estimates of the daily totals of SD. This algorithm will be referred to as the correlation algorithm.

1) SLOB ALGORITHM

The starting points of the Slob algorithm are parameterized estimates of the direct normal (I) and diffuse (D) irradiance for cloudless conditions. The expression for I reads (following Linke 1922; Kasten 1980)

$$I = \left(\frac{r_0}{r}\right)^2 I_0 e^{-T_L/(0.9 + 9.4\mu_0)}, \quad (1)$$

where r_0 and r are the mean and actual earth–sun distances, respectively, and I_0 is the solar constant (1366 W m^{-2}; Liou 2002); T_L is the Linke turbidity factor (Linke 1922), which is the ratio of the total atmospheric optical thickness to the Rayleigh optical thickness. It is therefore a dimensionless quantity that represents the impact of the true atmosphere on solar radiation with respect to a clean and dry atmosphere without trace gases and aerosols. The cosine of the solar zenith angle (θ_0) is indicated by μ_0.

By means of (linear) regression techniques, Slob and Monna (1991) found the following expressions for the estimation of the diffuse irradiance:

$$D/G_0 = \begin{cases} 0.2 + \mu_0/3 & \text{for} \quad 0.1 \le \mu_0 < 0.3 \\ 0.3 & \text{for} \quad \mu_0 \ge 0.3. \end{cases} \quad (2)$$

All radiation components are normalized by $G_0 = \mu_0(r/r_0)^2 I_0$, the downward solar irradiance on a horizontal surface at the top of the atmosphere. A period is now said to be sunny if the measured normalized global irradiance (G/G_0) exceeds the lower limit for cloudless conditions, $(G/G_0)_{lim}$, which equals

$$(G/G_0)_{lim} = \mu_0 I/G_0 + D/G_0. \quad (3)$$

By means of adjusting T_L, the parameterization of I, as given by Eq. (1), has been chosen in such a way that

$(G/G_0)_{\text{lim}}$ is only exceeded in the presence of direct radiation, which indicates a sunny period.

The measured difference between the minimum (G_{min}) and the maximum (G_{max}) value of the global irradiance during a 10-min interval is used to determine whether or not there has been a temporary eclipse of the sun by clouds. Large differences between G_{min} and G_{max} within a 10-min interval indicate the presence of broken clouds, because the global irradiance will be low when the direct solar beam is blocked, and high when the sun is visible. Even in cases where the sky is overcast, the difference between G_{min} and G_{max} is usually larger than under a cloudless sky, because of variations in cloud optical thickness.

A full description of the algorithm is given in the appendix. The algorithm is applied to 10-min mean measurements of global irradiance, giving values of the fraction (f) of sunshine for each interval ($0 \le f \le 1$). The sunshine duration (in minutes per 10-min interval) is then obtained by multiplying f by 10. According to Slob and Monna (1991), the uncertainty in SD using the Slob algorithm is about 0.6 h for daily sums.

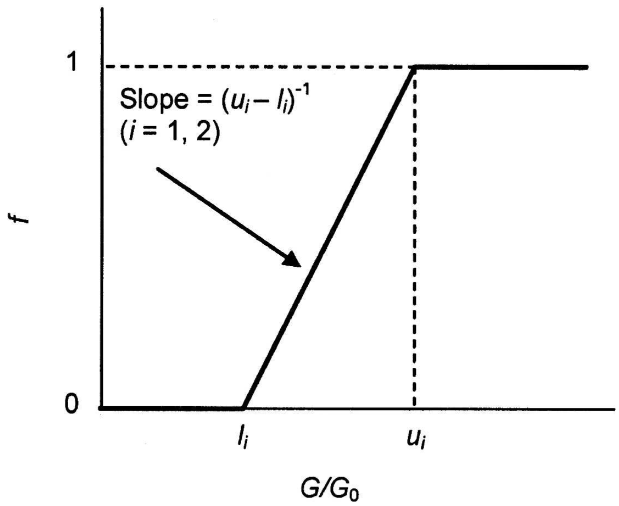

FIG. 2. Schematic representation of the correlation algorithm for the estimation of sunshine duration from global irradiance measurements [see Eq. (4)]. On the vertical axis the fractional sunshine duration (f) is given; on the horizontal axis the normalized global irradiance is given (G/G_0). The lower limit for G/G_0 below which $f = 0$ is indicated by l_i; the upper limit for G/G_0 above which $f = 1$ is indicated by u_i. The index i indicates a separation for μ_0 in two intervals: $\mu_0 < 0.3$ and $\mu_0 \ge 0.3$.

2) CORRELATION ALGORITHM

The correlation algorithm is based on a direct correlation between pyrheliometric values of f (derived from summation of sunshine seconds) and 10-min mean values of the normalized global irradiance G/G_0 (Fig. 2). The algorithm consists of a lower limit (l) for G/G_0 below which there is no sunshine ($f = 0$) and an upper limit (u) above which 10-min intervals are labeled as completely sunny ($f = 1$). Between the limits, the sunshine duration is linearly related to the normalized global irradiance. The algorithm distinguishes between two different μ_0 intervals ($\mu_0 < 0.3$ and $\mu_0 \ge 0.3$), because measurements showed that l and u are lower for smaller solar elevation angles. For the measurements considered, the best results are obtained for a separation at $\mu_0 = 0.3$. The functional form of the correlation algorithm is shown in Fig. 2 and is given by the following equation:

$$
\begin{array}{lll}
\mu_0 < 0.3: & G/G_0 < l_1 & \rightarrow f = 0 \\
 & l_1 \le G/G_0 < u_1 & \rightarrow f = (G/G_0 - l_1)(u_1 - l_1)^{-1} \\
 & G/G_0 \ge u_1 & \rightarrow f = 1 \\
\mu_0 \ge 0.3: & G/G_0 < l_2 & \rightarrow f = 0 \\
 & l_2 \le G/G_0 < u_2 & \rightarrow f = (G/G_0 - l_2)(u_2 - l_2)^{-1} \\
 & G/G_0 \ge u_2 & \rightarrow f = 1.
\end{array} \tag{4}
$$

The algorithm is again applied to every 10-min interval, but now only the mean measured global irradiance is needed. The sunshine duration (in minutes per 10-min interval) is again obtained by multiplying the fractional sunshine duration (f) by 10.

3. Solar radiation measurements

In this section, the solar radiation measurements used for this study are described. The direct normal solar irradiance is measured with a pyrheliometer (type: Kipp & Zonen CH1) and the global (and diffuse) irradiances are measured with pyranometers (type: Kipp & Zonen CM22, ventilated and heated). The instruments are part of the BSRN station of Cabauw in the Netherlands. Radiation measurements at this station are made by using BSRN methodology (Ohmura et al. 1998). BSRN protocols require sampling at a minimum of 1 Hz and storing derived statistics for

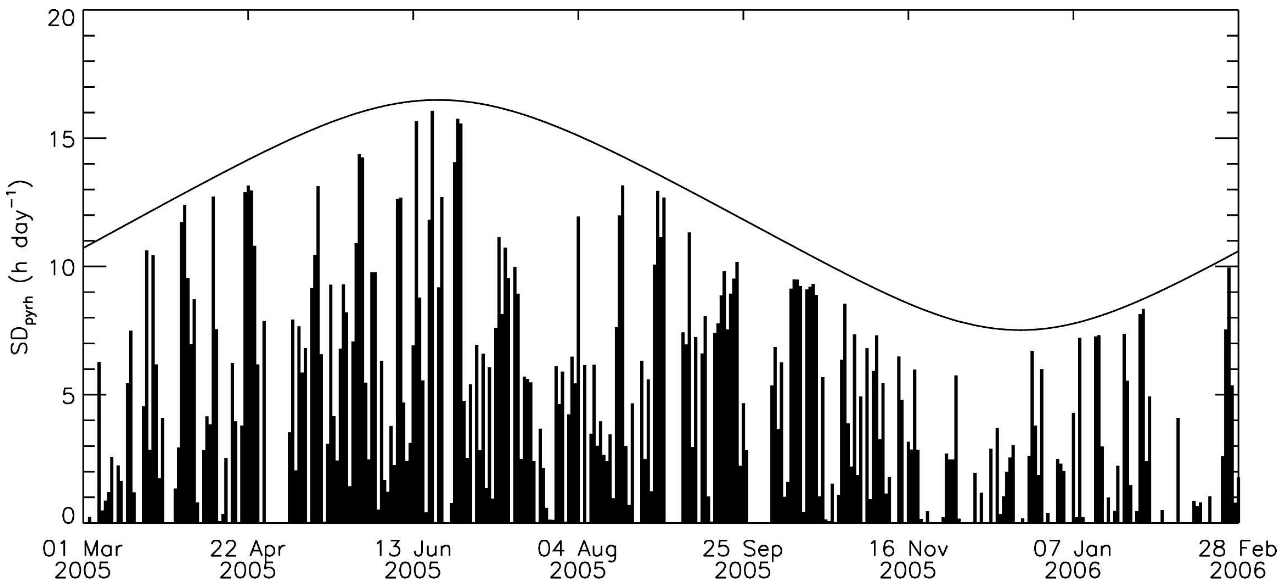

FIG. 3. Pyrheliometric daily sunshine duration (SD_{pyrh}; h day^{-1}) for Cabauw (Fig. 1) for the period March 2005–February 2006. The values are obtained from summation of sunshine seconds determined by means of application of the WMO threshold of 120 W m^{-2} for the direct solar irradiance. Also shown is the day length (solid line), which is defined as the time of the day for which $\mu_0 > 0$ (μ_0 was not corrected for atmospheric refraction).

minute periods. In Cabauw all 1-Hz measurements are stored allowing for the determination of sunshine seconds.

Solar radiation measurements for the period March 2005–February 2006 are used for the analysis of sunshine duration presented here. Before using the data of the different radiation instruments, the quality of the data was checked. If there were problems with the data acquisition system, power loss, or sun-tracking problems on a certain day, the entire day was omitted from the analysis. The remaining data were further checked by means of the quality control procedures described by Long and Dutton (2002), in order to flag and discard radiation data suspected of being erroneous. The procedures involve three quality checks concerning physically possible limits of the radiation measurements, extremely rare limits, and ratios of different radiation components. The quality checks are based on experience, empirical relations, and model calculations. It appeared that for the period March 2005–February 2006, 1.1% of the 10-min intervals did not meet the quality requirements. To make sure that differences in sunshine duration between the different methods are not caused by measurement errors, only data of good quality were used for the analysis.

4. Results

In this section, the different methods for the determination of sunshine duration are applied to the solar radiation measurements made in Cabauw between March 2005 and February 2006. Daily totals of sunshine duration are determined with the pyrheliometric and pyranometric methods. Furthermore, seasonal totals of sunshine duration are derived.

a. Pyrheliometric sunshine duration

A time series of daily totals of sunshine duration (h day^{-1}) as determined by means of the pyrheliometric method, is given in Fig. 3. Also shown in Fig. 3 is the day length, which is defined as the time that the sun is above the horizon ($\mu_0 > 0$) and represents the maximum possible daily SD. The cumulative sunshine duration according to the pyrheliometric method is 1429 h for the period March 2005–February 2006. For several reasons, this value is less than the climatological yearly sunshine duration in the Netherlands as reported in literature (1534 h; Heijboer and Nellestijn 2002). First, several days have been omitted from our analysis (see previous section), so the analysis presented here is not based on a full year of measurements. Second, the climatological value has been determined using an adjusted version of the Slob algorithm, which for reasons that will be discussed in section 5, significantly overestimates SD.

b. Pyranometric sunshine duration

In this subsection sunshine durations using the Slob algorithm and the correlation algorithm as described in

TABLE 1. Yearly totals of SD obtained by means of pyrheliometric measurements (WMO definition of SD; summation of sunshine seconds), the (adjusted) Slob algorithm (using 10-min mean measurements of global irradiance and corresponding maximum and minimum values), and the correlation algorithm (based on a direct correlation between the pyrheliometric SD and 10-min mean measurements of global irradiance). Cumulative and daily mean differences with respect to the pyrheliometric SD are given in the second and third columns. The standard error of the mean (σ_m) and the standard deviation of a single observation (σ) are given in the last two columns. The relation between σ_m and σ is as follows: $\sigma_m = n^{-1/2}\,\sigma$, where $n = 324$ (the number of samples or days).

	SD (h yr^{-1})	Difference (h yr^{-1})	Mean difference (h day^{-1})	σ_m (h day^{-1})	σ (h day^{-1})
Pyrheliometric method	1429	—	—	—	—
Slob algorithm	1357	−72	−0.22	0.05	0.82
Correlation algorithm	1437	8	0.03	0.03	0.53
Adjusted Slob algorithm	1436	7	0.02	0.04	0.69

section 2 will subsequently be compared with pyrheliometric sunshine durations.

1) EVALUATION OF THE SLOB ALGORITHM

According to the Slob algorithm, the cumulative sunshine duration is 1357 h, so this algorithm underestimates the pyrheliometric SD by 72 h on a yearly basis (Table 1). The daily mean underestimation amounts to 0.22 ± 0.05 h day^{-1} (the error represents the standard error of the mean of 324 samples). Figure 4a shows a scatterplot of the daily SD (h day^{-1}) as calculated by means of the Slob algorithm (SD_{Slob}) versus the daily pyrheliometric sunshine duration (SD_{pyrh}). Also shown in the figure are the 1:1 line and a linear fit through the data. The slope of the fit is 0.88, the offset is 0.31 h day^{-1}, and the corresponding standard deviation is 0.65 h day^{-1}. The cumulative underestimation by the Slob algorithm is mainly caused by the fact that SD_{Slob} underestimates SD_{pyrh} for $SD_{pyrh} > 5$ h day^{-1}, a result that is consistent with the findings of Slob and Monna (1991).

A frequency distribution of $SD_{Slob} - SD_{pyrh}$ is shown in Fig. 4b. The standard deviation of the distribution is 0.82 h day^{-1} (Table 1). Since negative differences occur more often than positive ones, Fig. 4b confirms that the Slob algorithm underestimates the pyrheliometric sunshine duration.

The underestimation is partly caused by the fact that, in the Slob algorithm, SD is by definition 0 for solar elevation angles below 5.7° (see appendix), whereas the WMO threshold of 120 W m^{-2} can already be exceeded for smaller solar elevation angles. Other causes of the underestimation are related to the parameterizations used in the Slob algorithm. For example, the lower limit for the global irradiance for cloudless conditions [Eq. (3)] may be estimated too high, resulting in an underestimation of sunny intervals. Further discussion on the

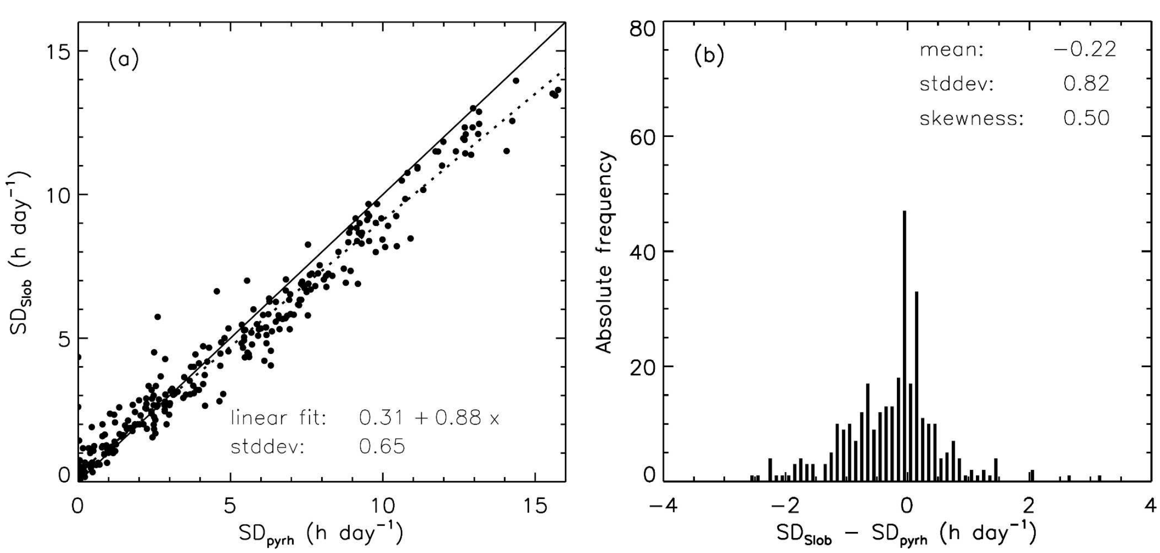

FIG. 4. (a) Daily sunshine durations (h day^{-1}) as calculated by means of the Slob algorithm (SD_{Slob}) vs corresponding pyrheliometric sunshine durations (SD_{pyrh}). Also shown are the 1:1 line (solid) and a linear fit through the data (dotted line). (b) Absolute frequency distribution of $SD_{Slob} - SD_{pyrh}$ (h day^{-1}).

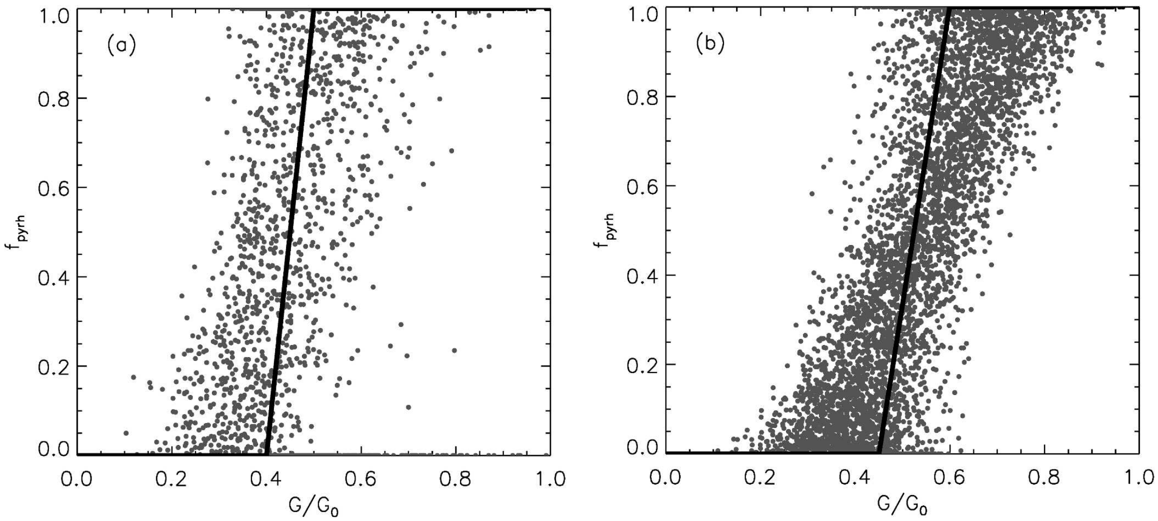

FIG. 5. Measurements (gray points) of the pyrheliometric fractional SD (f_{pyrh}) vs 10-min mean measurements of the normalized global irradiance (G/G_0) for (a) $\mu_0 < 0.3$ and (b) $\mu_0 \geq 0.3$. The solid lines indicate the fits used for the correlation algorithm [Eqs. (4) and Fig. 2] to directly estimate SD from global irradiance measurements. The fitted parameters for G/G_0 are $l_1 = 0.4$, $u_1 = 0.5$, $l_2 = 0.45$, and $u_2 = 0.6$.

performance and possible improvements of the Slob algorithm is given in section 5.

2) EVALUATION OF THE CORRELATION ALGORITHM

To apply the correlation algorithm, which directly relates SD to global radiation according to Eq. (4), values for the constants l_1, u_1, l_2, and u_2 need to be established. Figure 5a ($\mu_0 < 0.3$) and Fig. 5b ($\mu_0 \geq 0.3$) show scatterplots of the fractional pyrheliometric SD (f_{pyrh}) versus 10-min mean measurements of the normalized global irradiance. Optimal values for l_1, u_1, l_2, and u_2, giving best agreement between pyranometric and pyrheliometric daily SD, were found by systematic variation of the upper and lower limits for each μ_0 interval separately. This procedure resulted in the following values: $l_1 = 0.4$, $u_1 = 0.5$, $l_2 = 0.45$, and $u_2 = 0.6$. The parameterized forms of f as a function of G/G_0 for these constants are given by the solid lines in Figs. 5a and 5b. The lines might appear at first sight to give a nonoptimal representation of the data. However, this is caused by the fact that for most data f_{pyrh} equals either 0 or 1. For $\mu_0 < 0.3$ this is the case for 87% of the 10-min intervals and for $\mu_0 \geq 0.3$ for about 70% of the intervals.

The correlation algorithm gives a cumulative SD of 1437 h, which is only 8 h higher than the pyrheliometric SD (Table 1). Figure 6a shows a scatterplot of the daily SD (h day^{-1}) as calculated by the correlation algorithm ($\mathrm{SD_{corr}}$) versus the daily pyrheliometric sunshine duration ($\mathrm{SD_{pyrh}}$). The corresponding frequency distribution of $\mathrm{SD_{corr}} - \mathrm{SD_{pyrh}}$ is shown in Fig. 6b (the standard deviation of the distribution is 0.53 h day^{-1}). The figures indicate that, also on a daily basis, the correlation algorithm performs significantly better than the Slob algorithm. On a daily average basis there is no significant difference between $\mathrm{SD_{corr}}$ and $\mathrm{SD_{pyrh}}$ (mean difference $\pm$ standard error of the mean of 324 observations: 0.03 ± 0.03 h day^{-1}).

3) SEASONAL EVALUATION

From daily totals of sunshine duration seasonal totals can be derived. Figure 7 shows the seasonal SD according to the different methods (see also Table 2). Figure 7 shows that the Slob algorithm underestimates SD during most of the year, except for the winter season. In general we may state again that the correlation algorithm performs better than the Slob algorithm; Fig. 7 shows that is in particular true in the summer season when most sunshine hours are detected.

5. Discussion

The possibility of improving the Slob algorithm was investigated by means of a sensitivity analysis, in which the parameterizations as used in the algorithm were varied. Measurements of direct, diffuse, and global irradiance made at the BSRN station of Cabauw were used to adjust and optimize the parameterizations present in the Slob algorithm in order to obtain best agreement between the pyranometric and pyrheliometric daily SD. It appeared that with adjustments of the atmospheric turbidity T_L and parameterized diffuse irradiance [see Eqs. (1) and (2)] closer agreement with the pyrheliometric SD can easily be obtained. A full description of the sensitivity analysis and tuning proce-

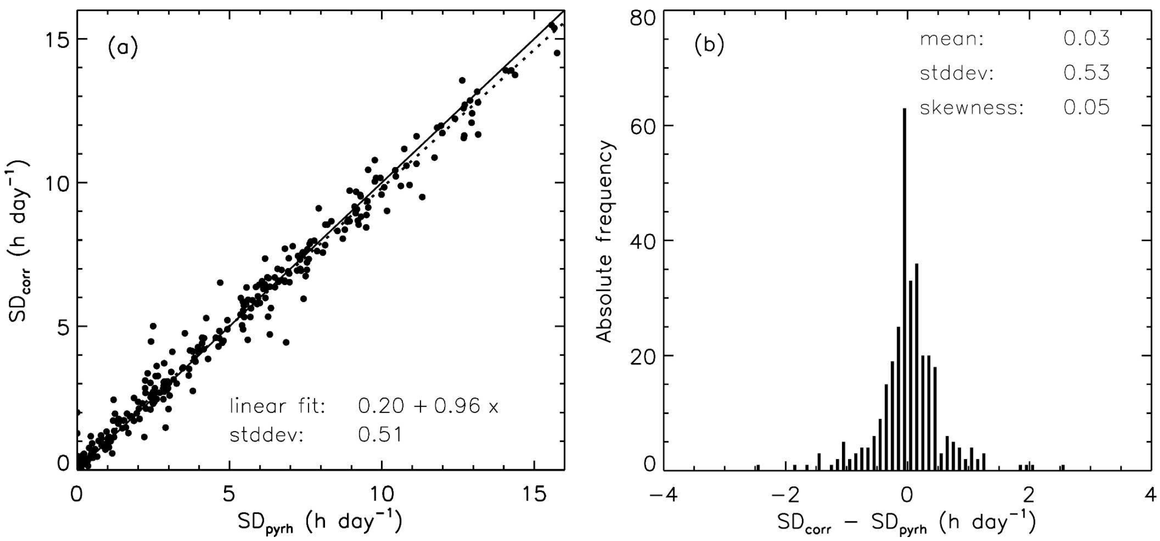

FIG. 6. (a) Daily sunshine durations (h day^{-1}) as calculated by means of the correlation algorithm (SD_{corr}) vs corresponding pyrheliometric sunshine durations (SD_{pyrh}). Also shown are the 1:1 line (solid) and a linear fit through the data (dotted line). (b) Absolute frequency distribution of $SD_{corr} - SD_{pyrh}$ (h day^{-1}).

dures can be found in Hinssen (2006). To obtain optimized SD values (indicated by SD_{Slob_adj}), the following adjustments were made to the Slob algorithm (cf. the appendix and Fig. A1).

- The minimum solar elevation angle for which SD can be positive was lowered from 5.7° to 2.9° ($\mu_0 = 0.05$ instead of $\mu_0 = 0.1$).
- The part of the algorithm for which $\mu_0 \geq 0.3$ was also applied to $0.05 \leq \mu_0 < 0.3$. This makes it possible to obtain fractional SD between 0 and 1 also for small solar elevation angles.
- The former adjustment implies two values (instead of one) of the Linke turbidity factor T_L for the interval $0.05 \leq \mu_0 < 0.3$. For these values we chose $T_L = 4$ and $T_L = 2.5$, respectively. For $\mu_0 \geq 0.3$ we chose $T_L = 5$ (instead of $T_L = 10$) and $T_L = 4$ (not changed).

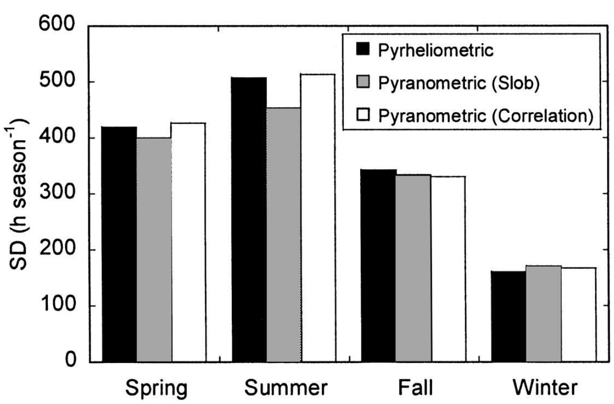

FIG. 7. Seasonal totals of sunshine duration (hours per season) as calculated by means of summation of sunshine seconds (pyrheliometric method), the Slob algorithm, and the correlation algorithm (pyranometric methods).

The following adjusted parameterizations of D/G_0 were used:

$D/G_0 = 0.02 + 1/(20\mu_0 + 4)$ for $\mu_0 < 0.3$ and $T_L = 4$.
$D/G_0 = 0.01 + 1/(20\mu_0 + 4)$ for $\mu_0 \geq 0.3$ and $T_L = 5$.
$D/G_0 = 0.3$ for $\mu_0 < 0.3$ and $T_L = 2.5$ and for $\mu_0 \geq 0.3$ and $T_L = 4$.

The statistics for SD_{Slob_adj} are listed in Tables 1 and 2. On a yearly basis SD_{Slob_adj} amounts to 1436 h. The difference $SD_{Slob\_adj} - SD_{pyrh}$ reduces to only 7 h for the whole period, or 0.02 ± 0.04 h on daily average basis (the error represents the standard error of the mean of 324 samples). These results, as well as the sea-

TABLE 2. Seasonal pyrheliometric sunshine durations (first line) and differences between the pyranometric and pyrheliometric sunshine durations.

	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
SD_{pyrh} (h)	419	507	343	161
$SD_{Slob} - SD_{pyrh}$ (h)	−19	−54	−8	9
$SD_{corr} - SD_{pyrh}$ (h)	8	7	−12	5
$SD_{Slob\_adj} - SD_{pyrh}$ (h)	7	−14	1	13

MAM = March–May. JJA = June–August. SON = September–November. DJF = December–February.

sonal differences, are comparable to those obtained by means of the correlation algorithm. However, it appears that, on a daily basis, the correlation algorithm performs slightly better, because the adjusted algorithm overestimates (underestimates) SD for small (large) solar elevation angles. Moreover, compared to the Slob algorithm, the correlation algorithm is simpler (fewer degrees of freedom; the correlation algorithm consists of only five variables), which makes it easier to tune the pyranometric SD to the pyrheliometric SD.

For the construction of SD products, such as the one shown in Fig. 1, KNMI has used since 1992 another adjusted form of the Slob algorithm (Bergman 1993; Schipper 2004) to estimate SD from global radiation measurements made at 32 stations in the Netherlands. Bergman (1993) adjusted the original Slob algorithm to find more agreement with SD values derived from the traditional Campbell–Stokes sunshine recorder. This was done to guarantee homogeneity of the Campbell–Stokes historical record of SD, which dates back to 1901. Comparison of SD values obtained by application of the KNMI operational algorithm and pyrheliometric SD values showed that the operational algorithm significantly overestimates the sunshine duration, by as many as 191 h for the period March 2005–February 2006 [a full description of this analysis is given by Hinssen (2006)]. This result gives indirect evidence for the well-known fact that the Campbell–Stokes recorder tends to overestimate the sunshine duration.

6. Summary and conclusions

The analysis presented here consists of an evaluation of different pyranometric methods for the determination of sunshine duration (SD) from global irradiance measurements. All pyranometric SD values are compared to SD values derived from pyrheliometric measurements of the direct solar irradiance (sampling frequency: 1 Hz) made at the Cabauw BSRN site in the Netherlands for the period March 2005–February 2006. Sunshine seconds, which add up to SD values in, for example, hours per day or hours per year, were derived by application of the WMO threshold of 120 W m^{-2} for the direct solar irradiance.

The so-called Slob algorithm (named after W. H. Slob, a former KNMI employee) allows one to estimate SD from 10-min mean measurements of global irradiance, and corresponding minimum and maximum values for this interval. Furthermore, the algorithm relies on parameterized estimates of the direct and diffuse irradiance, which are a function of Linke's turbidity factor T_L and the cosine of the solar zenith angle μ_0. The second algorithm considered here (correlation algorithm) directly relates SD to 10-min mean measurements of global irradiance (two correlations; one for $\mu_0 < 0.3$ and one for $\mu_0 \geq 0.3$). For the mentioned period, and with the omission of unreliable and bad data, the cumulative pyrheliometric SD amounts to 1429 h. The Slob algorithm gives 1357 h (underestimation of 72 h, or 5%) and the correlation algorithm gives 1437 h (overestimation of 8 h, or 0.6%). On a daily mean basis, the differences with respect to the pyrheliometric SD amount to -0.22 ± 0.05 h day^{-1} and 0.03 ± 0.03 h day^{-1} for the Slob algorithm and the correlation algorithm, respectively. With some tuning of the Slob algorithm (mainly by adjusting T_L), the yearly cumulative and daily mean differences can be reduced to 1436 h (+7 h or 0.5%) and 0.02 ± 0.04 h day^{-1}, respectively. The standard deviations of a single observation are 0.69 h day^{-1} for the adjusted Slob algorithm and 0.53 h day^{-1} for the correlation algorithm.

We conclude that it is possible to estimate daily sums of SD from 10-min mean measurements of global irradiance with a typical uncertainty of about 0.5–0.7 h day^{-1}. The uncertainty amounts to typically 0.5% for yearly cumulative sums. This result is in agreement with the findings of Oliviéri (1998) who found annual differences between pyranometric and pyrheliometric SD of less than 1%. It is important to note that the good agreement between the pyranometric and pyrheliometric SD was obtained after tuning both the Slob algorithm and correlation algorithm to the pyrheliometric SD. Potential users of the algorithms should be aware of the possibility that under different circumstances, for example, in a different climate or at different latitudes, the algorithms may not perform as well as presented here. We nevertheless believe that, with some tuning, preferably performed by means of reliable measurements from BSRN sites, it is possible to obtain similar results to the ones presented in this study. As for tuning, we emphasize that tuning of the correlation algorithm is much more straightforward than tuning of the Slob algorithm, because the former consists of only five variables, whereas the Slob algorithm is much more complicated (see the appendix).

As said before, all results presented here are based on the use of a 1-yr dataset of measurements of direct and global irradiance made at the Cabauw BSRN site in the Netherlands for the period March 2005–February 2006. Although the period represents a fairly normal year in terms of global radiation and sunshine duration for the midlatitude maritime climate of the Netherlands, it is desirable to extend the evaluation of the different algorithms to a multiyear dataset. Also the application of the algorithms to measurements obtained in different climates is considered to be worth-

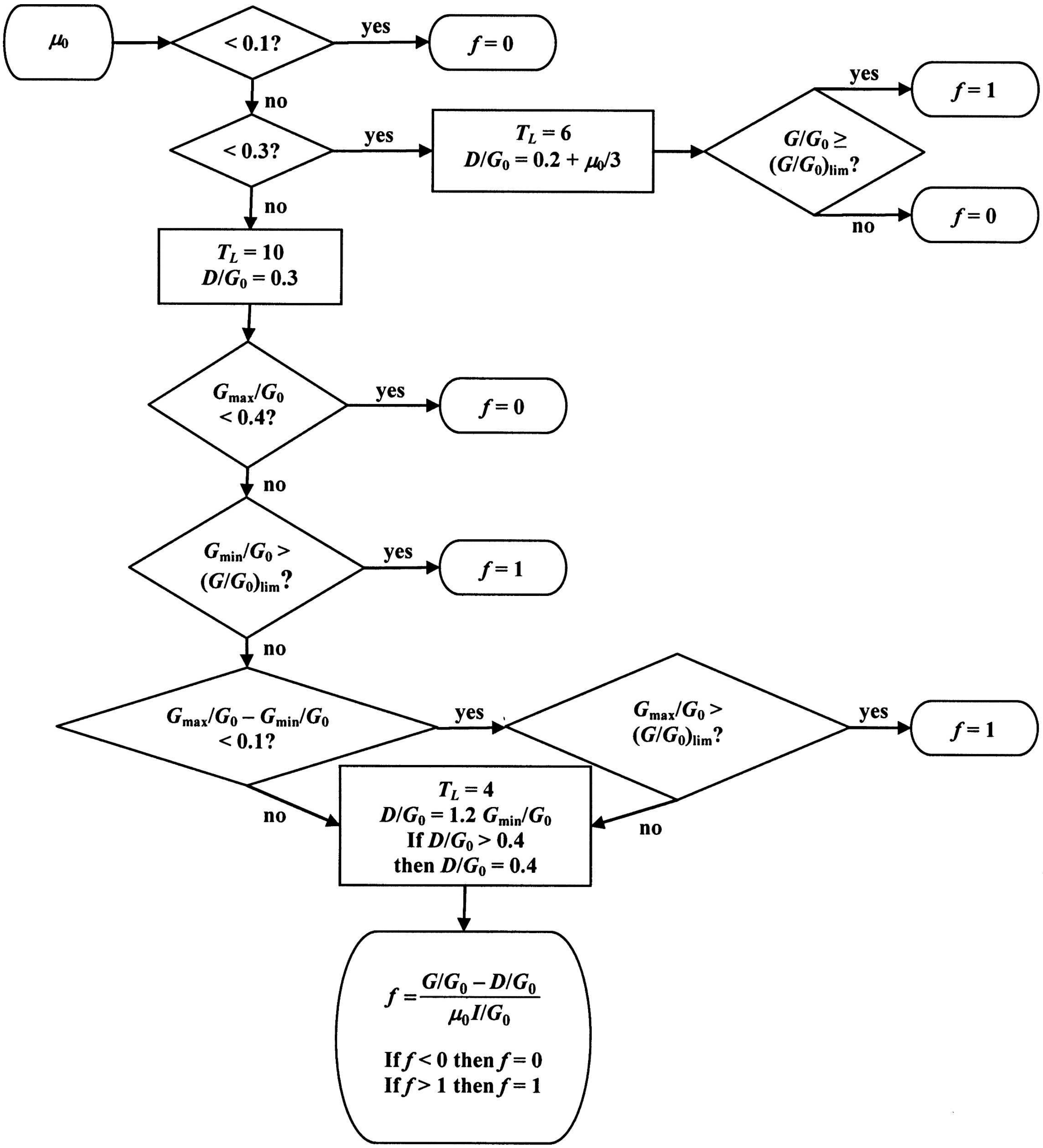

FIG. A1. Flow diagram of the Slob algorithm. The algorithm has been designed by Slob and Monna (1991) and is based on the use of mean, minimum, and maximum values of the measured global irradiance over a 10-min interval to estimate the fractional sunshine duration (f) for this interval. Furthermore, the algorithm relies on parameterized estimates of the direct and diffuse irradiance under cloudless conditions.

while. It seems particularly interesting to apply the correlation algorithm to polar or (sub)tropical regions, to investigate the performance of this algorithm under different solar elevation conditions.

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APPENDIX

The Slob Algorithm

Slob and Monna (1991) developed an algorithm to estimate the sunshine duration from global irradiance measurements [the algorithm is briefly described in WMO (2006); an extensive description is given by Hinssen (2006)]. The algorithm, summarized in the flow diagram in Fig. A1, is applied to 10-min mean and extreme values of the measured global irradiance, to obtain the fractional sunshine duration during each interval. The algorithm is based on parameterized estimates of the direct and diffuse irradiance for cloudless conditions [Eqs. (1) and (2)]. Furthermore, the variability of the measured global irradiance within a 10-min interval is used to obtain estimates of the fractional sunshine duration during (partly) cloudy conditions. For application of the algorithm, the following measurements are required.

G: 10-min mean of the global irradiance (W m^{-2}).

G_{min}: The minimum value of the global irradiance for the 10-min interval (W m^{-2}).

G_{max}: The maximum value of the global irradiance for the 10-min interval (W m^{-2}).

Other variables and equations that are used in the algorithm [see also Eqs. (1)–(3)].

f: Fractional sunshine duration as estimated by the algorithm. The sunshine duration in minutes per 10-min interval equals $10f$.

μ_0: Cosine of the solar zenith angle, calculated using the algorithm described by Michalsky (1988) (μ_0 was not corrected for atmospheric refraction).

I: Parameterized direct normal solar irradiance (W m^{-2}).

D: Parameterized diffuse irradiance on a horizontal surface (W m^{-2}).

T_L: Linke turbidity factor (dimensionless).

G_0: Top-of-atmosphere downward solar irradiance on a horizontal surface (W m^{-2}), calculated from the solar constant (1366 W m^{-2}) and the earth–sun distance.

$(G/G_0)_{lim}$: Estimated lower limit for the normalized global irradiance for cloudless conditions. This limit is only exceeded in the presence of direct radiation.

G_{max}/G_0: Variable used to detect overcast cases. If $G_{max}/G_0 < 0.4$ then $f = 0$.

G_{min}/G_0: Variable used to detect sunny cases. If $G_{min}/G_0 > (G/G_0)_{lim}$ then $f = 1$.

$G_{max}/G_0 - G_{min}/G_0$: Variable used to detect broken-cloud cases. For these cases the diffuse irradiance is estimated by means of $D/G_0 = 1.2\, G_{min}/G_0$, and (together with G and I) determines the fractional sunshine duration.

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