Experimental Verification of the Determination of Atmospheric Turbidity from Sunshine Recorders

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ABSTRACT

The feasibility of determining atmospheric turbidity from the burned traces of Campbell-Stokes sunshine recorders during cloudless sunsets and sunrises is examined experimentally. Results show that atmospheric turbidity can be determined in this way and can provide data for climatological research over the period of existing sunshine records. However, the measurements show a substantial uncertainty in the results if the properties of the used record cards are unknown. For networks of recorders, the method remains useful despite these limitations.

1. Introduction

In order to study climate and its changes, long-term records of various atmospheric parameters are needed. Most of these parameters have been recorded by climatological or meteorological networks for decades or longer. However, atmospheric turbidity as a measure of the atmospheric load of scattering and absorbing substances (other than air) is not included in these data. Consequently, efforts have been made either to install such networks [for instance, by the WMO (GARP, 1975)] or to use satellite measurements (Kästner and Quenzel, 1981). While these methods will be used in the future, data about past changes and trends are not readily available. Jaenicke and Kasten (1978) proposed a method for estimating turbidity from burned Campbell-Stokes sunshine recorder traces. This instrument has been used at many meteorological stations since its introduction into service late in the last century; there are stations in Western Europe, the USSR, Asia, Australia and North America which have such records for the last 100 years. This paper deals with an experimental verification of the proposed method and shows that, with some limitations, a data base is at hand which can be used to estimate past turbidity trends and changes.

2. Theory and experimental design

Sunshine recorders of the Campbell-Stokes type consist of a glass sphere mounted concentrically in a section of a spherical bowl. The diameter of the bowl is such that the sun's rays are focused on a card held by grooves in the spherical segment. During bright sunshine, a burned trace is produced on the card, the length of which is a measure of the duration of sunshine. The trace is burned if the sun is not covered by clouds and the radiation exceeds a certain threshold value I_{CS}. One major problem of the Campbell-Stokes recorder is the variability of this threshold value due to the environmental conditions, the transparency of the glass sphere and the properties of the card. Another problem is overburning of the card in conditions of intermittent sunshine. These limitations are well known and have been discussed by several authors (Baumgartner, 1979; Bider, 1959; Painter, 1981).

In the case of cloudless sunrises and sunsets, the solar radiation is weakened because of its long path through the atmosphere and/or because of atmospheric turbidity. This weakening may be so great that the threshold value I_{CS} is not reached and therefore no trace is burned on the card even when the sun is clearly visible. During cloudless sunrises or sunsets, the burned trace ends when the sun is at a certain angle α above the horizon. For this case, Jaenicke and Kasten (1978) developed the equation,

$$T_{CS} = (0.154\alpha + 1.05) \ln\left(\frac{I_0}{I_{CS}}\right), \qquad (1)$$

for values of α between 3 and 30°, where T_{CS} is the turbidity factor, measure of the turbidity for the complete solar spectrum; α is the solar elevation angle, calculated for the beginning or end of the burned trace for cloudless sky conditions; I_0 is the irradiance of extraterrestrial solar radiation; and I_{CS} is the threshold value of the recorder which must be exceeded to burn a trace on the card. If the station pressure p differs markedly from the standard pressure p_0, T_{CS} must be corrected by the factor p_0/p. For I_0, the actual earth–sun distance must be taken into account. The turbidity factor determined by this method is equivalent to the Linke turbidity factor T_T

for the complete solar spectrum; T_T usually is measured by pyrheliometers without any filter. Knowing the water vapor content of the air, T_T (T_{CS}) can be converted easily to the aerosol optical depth.

Our measurements were made in Mainz, a city in the industrialized Rhein–Main area of West Germany. Here, $T_T \approx 5$; thus the sun stops burning a trace on the recorder card within the limits given for α. Obstacles on the horizon are below 2° elevation, thus sunrises and sunsets are unobstructed.

The irradiance of direct normal solar radiation was measured with a Linke–Feussner pyrheliometer. These data were used to determine the I_{CS} values of the simultaneously used sunshine recorders and to evaluate the turbidity factor T_T using the so-called pyrheliometer equation (Kasten, 1980).

Four sunshine recorders of the Campbell-Stokes type were used to test four types of cards.

1) Dark-blue cards, sold by Lambrecht, Göttingen, Germany. These cards are recommended for use at stations of the German Meteorological Service (DWD).

2) Light-blue cards, sold by the French Meteorological Office (Centre Technique et du Materiel, Trappes-Cedex, France). This type is recommended by WMO (1971).

3) Black cards, obtained from DWD stations. These cards are used at most meteorological stations of the DWD.

4) Black cards, used at stations of the Austrian Meteorological Service (Zentralanstalt für Meteorologie und Geodynamik, Vienna, Austria).

These four types are also used at stations of other meteorological services, sometimes with some slight deviations in color. The problem is that many services do not have exact instructions for the production of the record cards, so that over the years the color can change. This may also be the explanation for the discrepancy between the cards recommended and actually used by the DWD. By the use of these four types of record cards, we hope to cover the whole color spectrum.

The measurements started in October 1980 and continued through 1981. First, the four sunshine recorders were used with the same cards to ensure that there were no differences in the apparatus. During the whole period, 83 cloudless sunrises or sunsets were observed. The actual number of comparisons, however, varies depending on the availability of instruments and cards of various origins. Details of the experimental results are described elsewhere (Helmes, 1982). Because of the limited data base, a careful statistical examination has been carried out and will be presented in connection with the results.

3. Results

Table 1 shows the I_{CS} values for the four different cards, determined by comparison with the pyrheliometer. As in other experiments (e.g., Baumgartner, 1979), the mean threshold value during sunrise is greater than that during sunset. This is caused by atmospheric water absorbed by the cards during the night (Baumgartner, 1979; Bider, 1959). However, because of the limited data set available to us, the difference in I_{CS} between sunrise and sunset was of no statistical significance (F-test and t-test). For this reason, Table 1 shows only mean values, not differentiated between sunrise and sunset for I_{CS}.

TABLE 1. Mean threshold value (I_{CS}) and standard deviation [$S(I_{CS})$] obtained from n measurements. The percentage given under L determines the statistical value of the statement: "I_{CS} is different from I_{CS}(WMO)."

Type of record card	I_{CS} (mW cm^{-2})	$S(I_{CS})$ (mW cm^{-2})	n	L (%)
Dark blue	20.517	3.485	47	—
Light blue	23.388	3.869	25	99.9
Black (DWD)	14.632	3.577	28	99.9
Black (Austria)	17.514	4.456	28	99.0

WMO-CIMO (1976) recommends a threshold value of $I_{CS}(\text{WMO}) = 20$ mW cm^{-2} for Campbell-Stokes sunshine recorders. The dark blue cards showed no statistically significant difference from the I_{CS}(WMO) value. All other cards, including that recommended by WMO itself, differ significantly (Table 1) from the recommmended I_{CS}(WMO) value.

Knowing the threshold irradiance for each card, the Linke turbidity factor T_{CS} can be calculated. The accuracy of these T_{CS} values is about 11% if we take the accuracy of I_{CS} as 17% and the accuracy of determination of sunshine duration as 0.1 h.

This error of 11% in determining T_{CS} is comparable to that for determining T_T from spectral photometer measurements. Typically, the following equation is used (Valko, 1967):

$$T_T = [\tau_D(500) + 0.54] \times [1.75 \log(W/m_R + 0.1) + 14.5] - 5.4,$$

where $\tau_D(500)$ is the optical depth at 500 nm wavelength, W the precipitable water (cm), and m_R the air mass. The precipitable water must be estimated, thus introducing considerable uncertainty.

In the following, the turbidity data (T_{CS}) determined by the burned trace method are compared with those determined by pyrheliometer (also called actinometer) (T_A). Figure 1 shows the data points for all comparisons. The regression line

$$T_A = 1.136T_{CS} - 0.619 \quad (2.8 < T_{CS} < 8.2) \quad (2)$$

is slightly off unity in the limited range of the comparison. This range is 3 to 30° solar elevation. Table 2 shows the corresponding solar elevation angle α for selected values of T_{CS} [Eq. (1), using $I_0 = 137$ mW cm^{-2}, $I_{CS}(\text{WMO}) = 20$ mW cm^{-2}]. This shows that $T_{CS} = 2.8$ is the lowest turbidity observable with

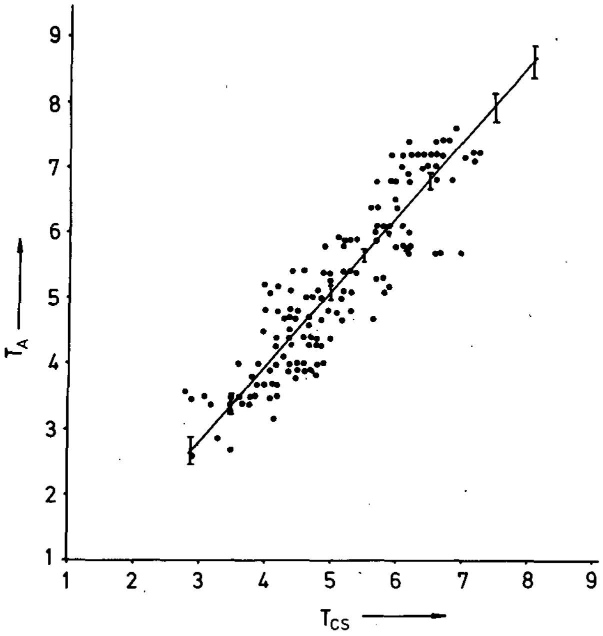

FIG. 1. Turbidity determined with a pyrheliometer T_A as a function of turbidity determined with the burned trace method T_{CS}, where T_{CS} is calculated using the individual threshold values I_{CS} of Table 1. The regression line is given by Eq. (2). The error bars show the confidence intervals of selected T_A values on the regression line.

the method, and $T_{CS} = 11$ the largest. In addition, Table 2 gives values of T_A calculated from Eq. (2), and the absolute difference ΔT. For all values of T_{CS}, the relative difference remains within 4%, showing the value of the method in comparison with others. Application of a statistical t-test comparing T_{CS} determined from the individual cards and directly-measured T_A shows no significant systematic difference.

If the proposed method for determining atmospheric turbidity from Campbell-Stokes sunshine recorders is applied to historical data, the threshold value I_{CS} usually is unknown. How does this influence the results and accuracy? To answer this question, all our measurements have been evaluated using the value $I_{CS}(\mathrm{WMO}) = 20$ mW cm^{-2} proposed by WMO. The results are shown in Fig. 2. The regression line then is

$$T_A = 1.046T_{CS} - 0.050. \qquad (3)$$

The scatter of the data points is greater than for individual I_{CS} values, of course. The regression line, however, is closer to unity and T_A and T_{CS} are not statistically different. This statement cannot be generalized because it is influenced by our selection of cards. However, it does give an impression of the usability of the proposed method for the evaluation of atmospheric turbidity from sunshine recordings over a network of stations (with cards of various origin) or for long time series (if cards changed with time).

Our data permit the determination of an experimentally derived equation similar to Eq. (1):

$$T_{CS} = (0.176\alpha + 0.893)\ln\left(\frac{I_0}{I_{CS}}\right). \qquad (4)$$

A new calculation of the T_{CS} values can be made with Eq. (4). Comparison with the T_A values results in a new regression equation, analogous to (2), but a statistical difference between this new regression line and the line from (2) cannot be shown. For this reason, we conclude that Eq. (1) can be used for the calculation of atmospheric turbidity.

TABLE 2. Selected values of the Linke turbidity factor T_{CS} determined from Campbell-Stokes recorders and T_A from actinometers, and the solar elevation angle α calculated from Eq. (1) using $I_0 = 137$ mW cm^{-2} and $I_{CS}(\mathrm{WMO}) = 20$ mW cm^{-2}. In addition, the absolute difference ΔT and the relative difference $\Delta T/T_A$ (percent) are given.

T_{CS}	T_A	$\lvert\Delta T\rvert = \lvert T_{CS} - T_A\rvert$	$\Delta T/T_A$ (%)	α (deg)
2.8	2.88	0.08	3	2.6
3.0	3.09	0.09	3	3.3
4.0	4.13	0.13	3	6.7
5.0	5.18	0.18	3	10.1
6.0	6.23	0.23	4	13.4
7.0	7.27	0.27	4	16.8
8.0	8.32	0.32	4	20.2
9.0	9.36	0.36	4	23.6
10.0	10.41	0.41	4	26.9
11.0	11.46	0.46	4	30.3

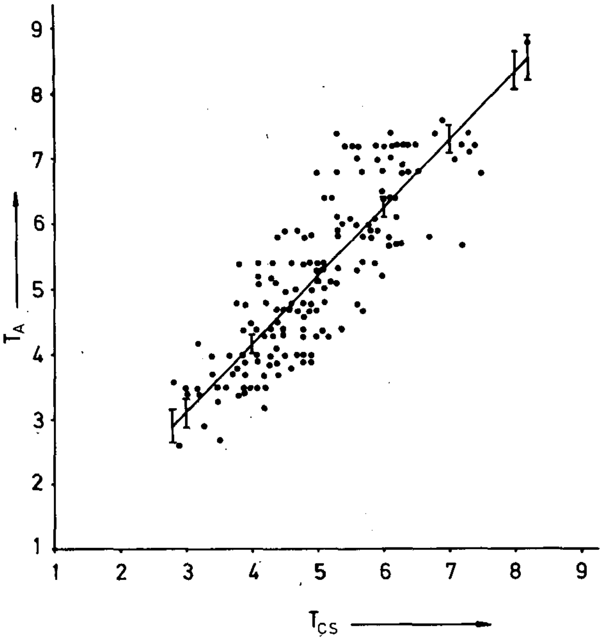

FIG. 2. Turbidity T_A as a function of T_{CS}, where T_{CS} is calculated using $I_{CS} = 20$ mW cm^{-2} for all cards. The regression line is given by Eq. (3). The error bars show the confidence intervals of selected T_A values on the regression line.

4. Conclusions

Experiments have shown that the theoretically-derived equation (1) can be used successfully for obtaining atmospheric turbidity from Campbell-Stokes sunshine recorder records for cloudless sunrises and sunsets. If the irradiance threshold of the record cards is known, then the accuracy is comparable to other, more direct methods such as the actinometer. If the threshold is unknown, a useful application can be expected only for averages. For a world-wide application, the influence of cloudiness must be considered. To solve this problem, further investigations have to be made.

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