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STATISTICAL MODEL OF DIFFUSE SOLAR RADIATION FOR TEMPERATE CLIMATE OF CENTRAL EUROPE

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Abstract

The studies of solar radiation, its intensity, and its structure are among the key issues addressed by meteorologists and climatologists. The inflow of solar radiation is crucial to the functioning of the Earth's climate system. Currently, the most commonly observed characteristic of solar radiation is its global value (*Kglob*). However, for numerous application studies e.g. in human bioclimatology, agroclimatology, solar energy or urban climate, there are required information on the seasonal pattern and spatial distribution of individual radiation fluxes: direct (*Kdir*), diffuse (*Kdif*), and reflected from the ground surface (*Kref*). Thus the aim of the current research is to propose a statistical model for determining the *Kdif* values for the climate zone of Central Europe based on available observations of global solar radiation. The model uses the Ångströmclearness index (*ACI*) which illustrates the attenuation of global solar radiation reaching the Earth's surface relative to its intensity at the upper boundary of the atmosphere. The development of a statistical model consisted of two stages: model development and model verification with the use of the set independent observational data representing lowland area of Poland (Dfb climate zone) as well as Beskid Sądecki Mts. (Dfc climate zone). The applicability of the model was also tested for other climate zones (southern Vietnam and central Mongolia). The results indicate that the proposed *ACI*-based model accurately approximates the amount of diffuse radiation for the lowland region of Central Europe. The method provides the satisfactory *Kdif* approximation in mountainous regions. The study results suggest also that the proposed *ACI*-based *Kdif* estimation model can be applied to other climate zones as tested for Aw zone of southern Vietnam, and Csa zone of central Mongolia.

Keywords

diffuse radiation fraction • Central Europe • statistical modelling

Introduction

The structure of solar radiation fluxes has been the subject of scientific investigation for many decades (Paszyński et al. 1991). In climate research, it is crucial to understand the seasonal pattern and spatial distribution of individual radiation fluxes: direct (*Kdir*), diffuse (*Kdif*), and reflected from the ground surface (*Kref*). These constitute

the basic components of the shortwave radiation balance, i.e. the amount of absorbed radiation (*K*) which is the difference between the fluxes reaching the ground surface (i.e. the global solar radiation, *Kglob*=*Kdir*+*Kdif*) and the radiation flux reflected from the surface. Information on the intensity of individual radiation fluxes is crucial in applied research, e.g. in human bioclimatology (Kozłowska-Szczęsna et al., 1997; Kozłowska-Szczęsna & Błażejczyk, 1998), agroclimatology (Bryś & Bryś, 2019), solar energy (Nelken & Żmudzka, 2017), urban climate studies (Landsberg, 1981; Paszyński et al., 1991; Uscka-Kowalkowska, 2019).

Direct measurements of diffuse radiation are not commonly conducted and at majority of meteorological stations the global solar radiation is only measured. Therefore, indirect methods for determining *Kdif* are sought (Orgill & Hollands, 1977; Iqbal, 1979; Erbs et al., 1982; Bristow & Campbell, 1985; Boland et al., 2001; Ridley et al., 2010; Beyazit et al., 2020). For Poland, located in the temperate transitional climate zone, Błażejczyk (1997) has found that under cloudless sky conditions the fraction of *Kdif* in global radiation (*fdif*) is a function of the sun's elevation above the horizon (*hs*), whereas for overcast sky conditions, it is a function of the global solar radiation intensity (*Kglob*). The determined regression equations differ depending on the type of cloud cover. The relationship between diffuse radiation and cloud cover type was also pointed out by Kasten & Czeplak (1980) for northern Germany (Hamburg) as well as by Wojciechowska (2023) for southern Poland (Carpathians).

Beyazit et al. (2020), Boland et al. (2001), Chandel & Aggarwal (2011) as well as Erbs et al. (1982) link the amount of diffuse radiation to the atmospheric clarity index (*CI*), which represent the fraction of the actual global solar radiation on the surface of the Earth in the theoretical maximum (under clear sky) radiation. *CI* allows for a reliable estimate of the value of diffuse radiation. Very valuable review of existing approximation methods was done by Beyazit et al. (2020) who discuss applicability of 15 methods. Majority of them can be applied to hourly means of radiation fluxes. Similar review of 97 models was made by Wang et al. (2019) on an example of Chinese stations. In addition to the presence of clouds, the *CI* value is influenced by a number of factors, including the content of water vapor and pollutants in the atmospheric air (Krawczyk, 1968; Heim et al., 2007), and at low solar positions above the horizon, even with a cloudless sky, the so-called optical mass of the atmosphere (*m*) is considered. This is a dimensionless index reflecting the thickness of the air layer through which solar rays must pass and the *m* value is a function of the angle of incidence of the solar rays.

A complementary measure of atmospheric transparency to *CI* is the Linke turbidity factor (*TL*). It is recommended by the World Meteorological Organization (WMO) for estimating diffuse radiation (WMO 2023). This topic will be discussed in more detail in the description of data and research methods.

Last year's brought new group of methods that can be widely used for assessment of global and diffuse radiation, namely WRF-Solar models (Weather Research and Forecasting). Their validation was made by Lu et al. (2023) for China. Their results show that WRF-Solar models provide highly accurate radiation in clear sky conditions. Under cloudy conditions the comparisons show poor concordance with observed radiation.

Currently, the most commonly observed characteristic of solar radiation is its global value (*Kglob*). *Kglob* intensity is sufficient to characterize general climate properties. However, numerous studies in bioclimatology or detailed studies of solar conditions and sunshine duration require information on the amount of direct radiation (*Kdir*) and diffuse radiation (*Kdif*).

Thus the aim ofthe current research is to discuss and topropose a statistical model for determining the *Kdif* value for the area of Central Europe based on available observations of global solar radiation. The model uses the Clearness Index according to Ångström concept (*ACI*) which illustrates atmospheric transparency, i.e. the attenuation

of global solar radiation reaching the Earth's surface relative to its intensity at the upper boundary of the atmosphere (WMO No-8, 2023). In the present paper *ACI* is called "Ångström Clearness Index". The applicability of proposed model was compared with some other approximation methods which are relevant to momentary observational data sets.

Materials and methods

The development of a statistical model for determining diffuse radiation consisted of two stages. The first stage (model development) combined observational data on global (*Kglob*) and diffuse (*Kdif*) radiation measurements conducted between 1980 and 1996 at various locations: Dźwirzyno, Borowa Góra, Udziejek, Supraśl and Głuchołazy (Fig. 1; Tab. 1). According to the Köppen-Geiger climate classification (Peel et al., 2007) all stations represent Dfb climate zone with warm summer (up to 4 months with temperature > 10°C). Dfb climate zone covers great area of central and eastern Europe. The database includes nearly 4048 observations conducted under various cloud cover conditions (from 0 to 8 degrees) and at various sun altitudes (from 0.5 to 63 degrees). The observations made in very low Sun altitude were excluded from dataset. *Kglob* and *Kdif* measurements were made with the use of pyranometer-and-galvanometer sets which were calibrated by the Institute of Meteorology and Water Management (IMGW). For the measurements of *Kdif* the pyranometer was shaded manually. Observations were made every 30 or 60 minutes and they represent momentary intensities of *Kglob* and *Kdif* for the particular Sun altitude and cloud cover.

The contribution of diffuse radiation to total radiation (*fdif*) was calculated as follows:

$$fdif = Kdif / Kglob \quad (1)$$

The approximation of the rate of diffuse radiation bases on the clearness index proposed by Ångström (*ACI*):

$$ACI = Kglob / (I0 \cdot \sin hs) \quad (2)$$

where:

I0 – is the solar constant (according to WMO = 1367 $W \cdot m^{-2}$), and *hs* is Sun elevation (°).

Table 1. Essential information of locations used in the study

Location	Latitude	Longitude	Station elevation [m a.s.l.]	Period of observation	Number of observations
Locations used in the phase of model construction					
Dźwirzyno	54°10'°	15°24'	5	June 1980	275
Borowa Góra	52°29'°	21°01'	110	May 1994 July 1995 Sep 1996	2792
Udziejek	54°16'	22°53'	240	June 1988 July 1989	282
Supraśl	53°13'	23°14'	150	June-July 1994	543
Głuchołazy	50°19'	17°23'	285	August 1992	156
Locations used in the phase of model validation					
Warsaw	52°14'	20°59'	107	Jan-Dec 2003	364
Muszyna	49°23'	20°53'	560	June 1993	418
Locations used in regional comparisons					
Mongolia	47°59'	107°26'	1350	Aug 1988	75
Vietnam	12°44'	108°04'	530	March 1988	173

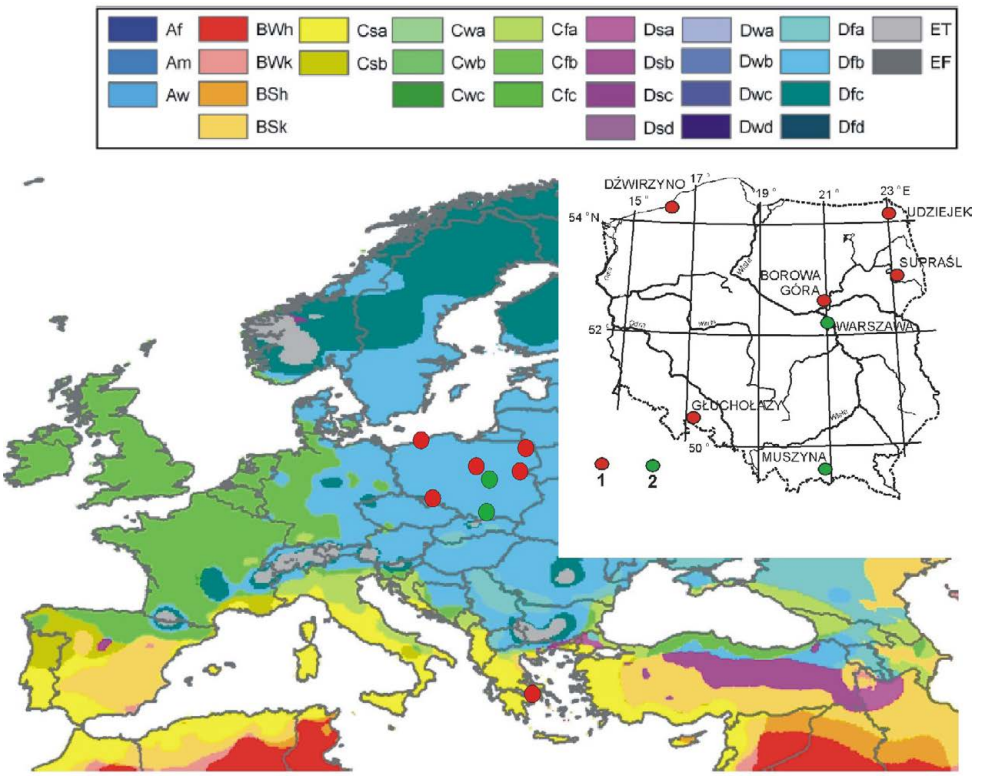


Figure 1. Location of stations with observations of diffuse and global solar radiation on the background of Köppen-Geiger climate classification; 1 – stations used for model development, 2 – stations used for model verification

Source: Adapted from: Peel et al. (2007).

There were searched statistical relationships between observed *fdif* and *ACI* values. In an effect the *fdif_ACI* model was developed.

The second stage of the study (model verification) utilized observational data of *Kglob* and *Kdif* from the IGiPZ PAN weather station on Twarda Street in Warsaw. The model, developed based on observational data, was also tested for its applicability to mountainous areas of Central Europe (Fig. 1, Tab. 1; Muszyna, Beskid Sądecki – Dfc climate zone) and other climatic zones (southern Vietnam – Aw climate zone; central Mongolia – Csa climate zone; Peel et al. 2007). The database included approximately 364, 418, 173, and 75 observations, respectively, conducted in different seasons, at different sun heights, and under varying cloud cover conditions (from 0 to 8).

At the stage of verification of the *fdif_ACI*model, approximate values of scattered radiation were calculated – (*Kdif_ACI*) and compared with the measured values of*Kdif*.

$$Kdif_ACI = fdif_ACI \cdot Kglob \quad (3)$$

For the comparison there were also calculated diffuse radiation values with the use of two alternative method: Slob and Monna (*Kdif_TL*) which bases on the Linke turbidity factor (*TL*) and Boland (*Kdif_Bol*) based on clarity index CI.

In the Slob-Monna method for sun elevation (*hs*) < 5.7° there is assumed that only diffuse radiation reach earth surface.

For $hs > 5.7°$ the modelled intensity of diffuse radiation ($Kdif_TL$) is calculated as follows:

$$Kdif_TL) = I \cdot D \qquad TL \tag{4}$$

where:

$$I = I0 \cdot e^{[-TL \,/\, (0.9 + 9.4 \cdot \sin hs)]} \tag{5}$$

TL -Linke turbidity factor (according to Fanjirindratovo et al, 2024 = 6 for $hs \leq 17.5°$ and = 4 for $hs > 17.5°$). The used *TL* are similar to those reported by Uscka-Kowalkowska et al. (2017) and not significantly influence *I* calculation.

$$DTL = (0.2 + \sin hs/\ 3) \quad \text{for } hs \leq 17.5°, \tag{6}$$

and

$$DTL = 0.3 \quad \text{for } hs > 17.5°.$$

In the Boland method (Boland et al., 2001), the contribution of diffuse radiation to global radiation is based on the clarity index *CI*. This approach is similar to the Ångströmclearness index, and because the authors did not provide a detailed method for determining the *CI*, the *ACI* values as presented in equation (2) was used in the calculations.

$$fdif_Bol = 1/[1+e^{(8.645 \cdot (ACI - 0.613))}] \tag{7}$$

and

$$Kdif_Bol = fdif_Bol \cdot Kglob \tag{8}$$

Both at the stage of creating the *fdif_ACI* model and at the stage of its validation, the statistical analysis was performed with the use of STATGRAPHICS Centurion XVI, version 16.2.04 software package.

Results

To create a statistical model approximating the contribution of diffuse radiation to global radiation the data from 4048 observations of these fluxes conducted at various locations in Poland were used. Figure 2a shows the distribution of row data used for the correlation between *fdif* and *ACI* fractions. The correlation coefficient is quite good (0.88). However, in the wide range of *ACI* fractions their concordance with observed *fdif* is not very high. Thus, the proposed model bases onthe distribution of mean, maximum, and minimum *fdif* values across successive ranges of the *ACI* (Fig. 2a). The greatest stability of *fdif* occurs at *ACI* values below 0.15, i.e., with low atmospheric transparency and*fdif*then ranges from about 0.93 to 1.0. At *ACI*s between 0.16 and 0.45, which are characteristic of variable low- and middle-level cloud cover, *fdif* values are characterized by a significant range of variability (from about 0.3 to 1.0, with mean values ranging from 0.8 to 0.98). The greatest *fdif* dispersion (from about 0.1 to 1.0) occurs at *ACI*s between 0.5 and 0.65. At high *ACI*

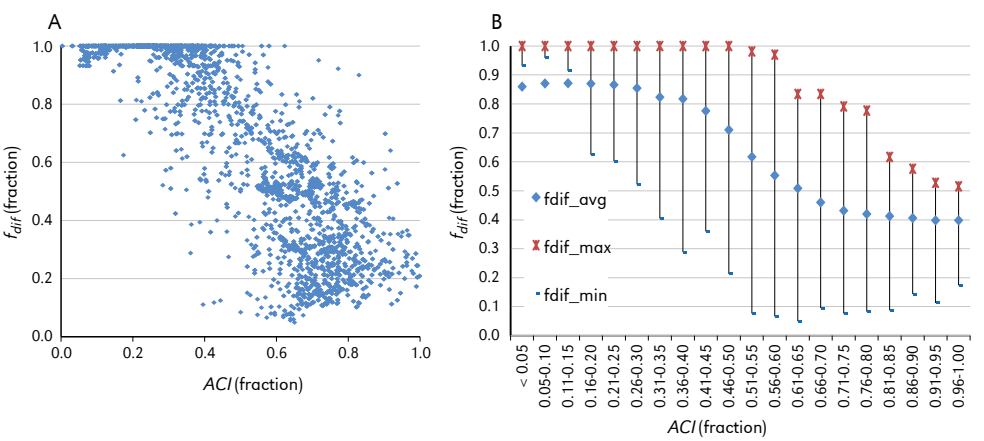


Figure 2. Distribution of raw *fdif* (A) and *ACI* data as well as average, maximum and minimum *fdif* values in subsequent *ACI* ranges (B)

(0.8-1.0), which indicate high transparency of the atmosphere, the share of diffuse radiation in its global amount is on average about 0.3, and the range of *fdif* values varies from 0.1 to 0.6.

The following 3rd order polynomial function was established to model the fraction of diffuse radiation (*fdif_ACI*) :

$$fdif_ACI = 0.85882 + 2.0004 \cdot ACI - 6.888 \cdot ACI^2 + 4.3587 \cdot ACI^3 \quad (9)$$

Thevalue of determination coefficient (R^2) of the above approximation is 99%, the standard error of estimation is 0.0308, and mean absolute error is 0.0238. The p-values of particular components of the model are equal to 0 at significance level of 95%. The accuracy of the above model was validated for independent set of observation from Warsaw (Tab. 2). The special dataset from 2002 dedicated to this validation was applied.

Table 2. Summary statistics of observed (*fdif*) and modelled (*fdif_ACI*) fractions of diffuse solar radiation, Warsaw, Central Poland

Characteristic	*fdif* (observed)	*fdif_ACI*(modelled)
n	347	347
Average	0.695	0.801
Standard deviation	0.301	0.210
Minimum	0.104	0.283
Maximum	1.000	1.000
Range	0.896	0.738

Since the interval does not contain the value 0, there is a statistically significant difference between the means of the two samples at the 95.0% confidence level. The correlation coefficient between observed – *fdif*- and calculated -*fdif_ACI* – fractions of difuse radiation is 0.87, standard error of estimation is 0.147, and mean absolute error is 0.111. There is a statistically significant relationship between *fdif*and *fdif_ACI* at the 95.0% confidence level (Fig. 3). Following high correlation between observed and calculated fractions of diffuse radiation the line of identity show well concordance between both values.

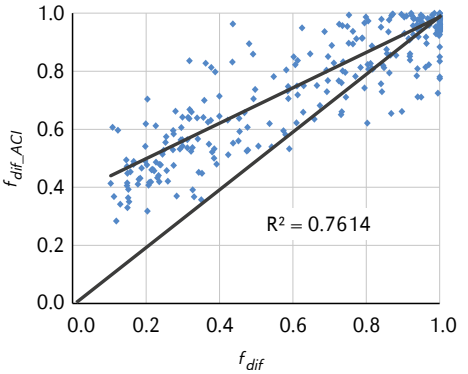


Figure 3. Relationships between observed (*fdif*) and modelled (*fdif_ACI*) fractions of diffuse solar radiation in global radiation; regression line is solid, identity line is dotted

The next step in validating the proposed *fdif_ACI* model was to apply it for calculation the *Kdif_ACI* values and comparing them with the measured diffuse radiation. At this stage of the study, diffuse radiation values were also calculated using the WMO-proposed Slob-Monna model (*Kdif_TL*) and the Boland model (*Kdif_Bol*). Comparison of those obtained from a series of independent data from Warsaw shows that the measured values are better approximated by models based on the clearness index (*Kdif_ACI*, *Kdif_Bol*) than on the turbidity factor (*Kdif_TL*). This is evidenced by both the correlation coefficients (0.93, 0.93, and 0.66, respectively) and the greater convergence with the identity line. The slope coefficients are 1.12 for *ACI*, 1.15 for the Boland's, and 0.69 for the *TL* method (Fig. 4).

The above statements are also confirmed by a comparison of basic statistical characteristics for the analyzed variables. There is no statistically significant difference between the means of *Kdif*and *Kdif_ACI*, as well as *Kdif_Bol*, at the 95.0% confidence level. This means that observed and modelled values of diffuse radiation are equal each other. For the means of *Kdif* and *Kdif_TL*, there is a statistically significant difference at the 95.0% confidence level (Tab. 3). Therefore, it can be assumed that for the lowland area of Central Europe, the proposed model for estimating

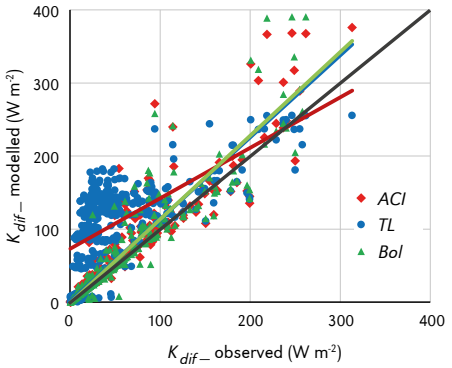


Figure 4. Comparison of the observed and approximated values of diffuse solar radiation obtained by various models: *ACI* – proposed by Author, *TL* – Slob-Monna, *Bol* – Boland; independent data from Warsaw (Dfb climate zone); regression linesare solid, identity line is dotted

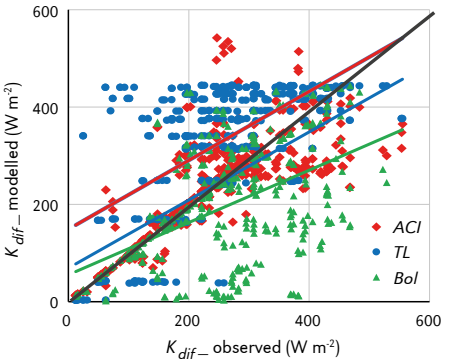


Figure 5. Comparison of the observed and approximated values of diffuse solar radiation obtained by various models: *ACI* – proposed by Author, *TL*– Slob-Monna, *Bol* – Boland; independent data from Muszyna (Beskid Sądecki Mts., Dfc climate zone); regression linesare solid, identity line is dotted

diffuse radiation, based on the Ångström clearness index (*fdif_ACI*), accurately approximates *Kdif* values both, when applying method proposed by Author and used Boland's algorithm.

In the Central Europeclimate zone, significant areas are covered by mountain ranges. Therefore, there was tested whether the model developed based mostly on data from lowland and foothillsstations could be applied to mountainous areas. Data collected in the Beskid Sądecki Mts. indicate that the error in estimating *Kdif* is greater here than for lowland areas (Fig. 5).

In the case of the Beskid Sądecki Mts. region, a comparison of the measured and calculated diffuse radiation values applying three examinedmethods shows less similarity than for the lowland region of Central Poland. The correlation coefficient for the studied variables for the *ACI*-based is 0.760 and 0.520 for Boland methods, while for the *TL*-based method it is r = 0.632. Figure 5 shows that the regression lines for *ACI* and *TL* are equally deviated from the line of identity, and slope coefficients are 0.699 and 0.700, respectively. The weakest slope coefficient was found for Boland's method (0.537). For all models, the difference between the means is statistically significant at the 95.0% confidence level. However, the mean values of diffuse radiation approximated using the Author's method are lower than the measured *Kdif* by only about 3 W·m^{-2}. In the case of the Boland model they are lower by 57 W·m^{-2}, and those obtained with the use of Slob-Monna method

Table 3. Summary statistics for compared variables, independent data from Warsaw

Characteristic	*Kdif*	*Kdif_ACI*	*Kdif_Bol*	*Kdif_TL*
n	364	364	364	364
Average	53.2	60.9	59.9	109.8
Standard deviation	56.8	68.5	69.8	59.2
Minimum	0.4	0.3	0.4	0.4
Maximum	313.2	376.1	400.4	255.5
Range	312.8	375.8	400.0	255.1

are higher than the measured ones by almost 72 W·m^{-2} (Tab. 4).

The final stage of validation of the *fdif_ACI* model is to test how it approximates diffuse radiation values in other climate zones. Data from studies conducted in the continental climate of central Mongolia (Csa climate zone) and the subtropical climate of southern Vietnam (Aw climate zone) were used for this purpose.

For both climate zones, mean diffuse radiation values approximated using the *fdif_ACI* model are closer to observed values than those determined based on *TL*. In the case of the continental climate of central Mongolia, mean diffuse radiation values are not statistically different between the *Kdif* and *Kdif_ACI* and *Kdif_Bol*at the 95.0% confidence level. However, the differences between *Kdif* and *Kdif_TL* are statistically significant. In the subtropical climate of southern Vietnam, for all tested approximation methods, the differences between measured and calculated values are statistically significant at the 95.0% confidence level (Tab. 5).

Comparing the regression lines for the observed vs. calculated diffuse radiation values shows that for the continental climate of Central Mongolia, the correlation coefficients are statistically significant for all approximation methods (0.700 for *ACI*, 0.530 for Boland, and 0.565 for *TL* models). Analysing the distributions of values, it is clear that the regression lines determined for *ACI* and *TL*based methods are similarly deviated from the identity line (0.455 and 0.446, respectively), while for Boland model, the slope coefficient is equal to 0.369. The correlation coefficients for the measured and calculated diffuse radiation values are statistically significant for the data series from southern Vietnam (0.640 for *ACI*, 0.608 for Boland and 0.547 for *TL* approach). However, the distributions of values of the compared variables show that the regression line determined for *TL* deviates significantly from the identity line. In the case of the *ACI*-based method, the regression line and the identity line are very close to each other (slope coefficients are 1.38 for *TL* as well as 0.946 for *ACI* and 0.798 for Boland) (Fig. 6).

Table 4. Summary statistics for compared variables, independent data from Beskid Sądecki Mts.

Characteristic	*Kdif*	*Kdif_ACI*	*Kdif_Bol*	*Kdif_TL*
n	418	418	418	418
Average	243.2	240.1	186.1	315.0
Standard deviation	118.5	111.3	120.5	139.5
Minimum	12.3	12.6	1.4	3.0
Maximum	555.2	541.8	446.0	444.1
Range	542.9	529.2	444.6	441.1

Table 5. Summary statistics for compared variables, independent data from Mongolia and Vietnam

Characteristic	Mongolia					Vietnam			
	Kdif	*Kdif_ACI*	*Kdif_Bol*	*Kdif_TL*		*Kdif*	*Kdif_ACI*	*Kdif_Bol*	*Kdif_TL*
n	75	75	75	75		173	173	173	173
Average	154.4	193.3	131.0	262.4		150.6	209.5	170.8	284.3
Standard deviation	132.5	85.6	80.7	103.6		92.2	109.7	94.4	171.3
Minimum	3.2	27.4	26.5	29.6		3.0	2.9	3.0	3.0
Maximum	514.0	357.5	346.1	400.1		366.0	421.0	424.0	480.0
Range	510.8	330.1	310.6	370.5		363.0	418.1	421.0	477.0

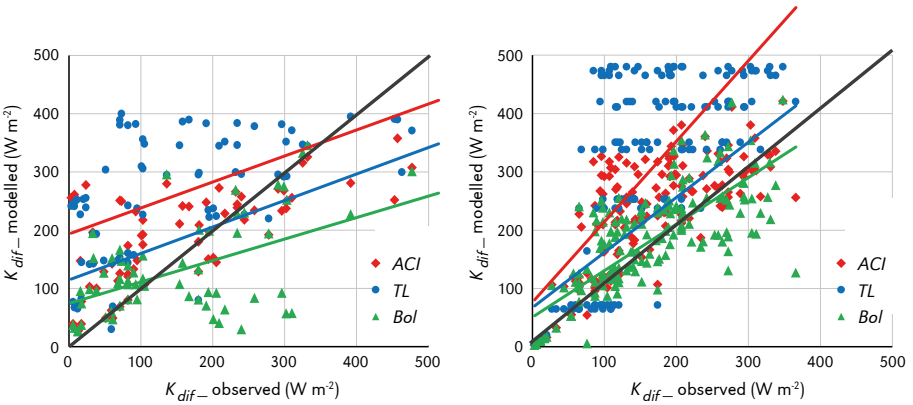


Figure 6. Comparison of the observed and approximated values of diffuse solar radiation obtained by various models: *ACI* – proposed by Author, *TL* – Slob-Monna, *Bol* – Boland; independent data from central Mongolia (Csa climate zone) and south Vietnam (Aw climate zone); regression linesare solid, identity line is dotted

Discussion

Research on estimating global and diffuse radiation fluxes has been conducted since the 1960s. The impetus for these studies came from the needs of the developing solar energy industry. One of the first methods in this area was the one proposed by Liu and Jordan (1960). It has been and continues to be used in numerous applied studies (Koussa et al., 2007; Tabet et al., 2014). However, this method applies only to monthly mean radiation data.

Daily or monthly values of radiation fluxes, most often under cloudless or slightly cloudy sky conditions, were the basis for studies carried out in Canada by Iqban 1979 and Tuller 1976. Data with a similar temporal resolution were also used by Erbs et al. 1982 and Beyazit et al. 2020. The relationships between *Kglob* and *Kdi f*obtained by them are of a general nature, not allowing the assessment of diffuse radiation for data with low temporal resolution (e.g. 10 min, which is required by the WMO method of estimating sunshine duration (WMO, 2023). They only allow for the estimation of the solar energy potential for a given region.

Data with a similar temporal resolution to that in the present paper, namely 15 minutes, were used in studies by Boland et al. (2001) and Ridley et al. (2010) based on several meteorological stations in Australia. The authors relied on the clarity index to estimate the fraction of diffuse radiation. The aforementioned authors proposed a logistic function to describe the relationships they found. It should also be noted that they used only clear-sky observations to build their model. For the lowland areas in Poland and in Vietnam, the Boland method yields similar results to the *ACI* based method proposed in the present study.

To validate the models applying for determining diffuse radiation the independent observational data were used. They show that the *ACI*-based model provides very good results for lowland Poland. In the climatic conditions of Central Poland, the approximated diffuse radiation values are close to the observed ones. The *Kdif* estimates for the Beskid Sądecki Mts. ridge and for the mountainous region in Mongolia are significantly weaker. One reason for this may be the phenomenon of radiation reflected from the slope surfaces reaching the valley bottoms (Błażejczyk, 1998; Kozłowska-Szczęsna et al., 2001; Szymczak & Błażejczyk, 2021). This radiation reaches the measuring instrument sensor in the form of diffuse radiation and increases the amount of total radiation. This phenomenon significantly disturb

relations between global and diffuse radiation and therefore the *ACI* values.

Conclusions

The proposed statistical model based on the Ångström clearness index (*ACI*) can be successfully used to estimate the amount of diffuse radiation in the climatic conditions of Central Europe. Testing results indicate that the proposed *ACI*-based model accurately approximates the amount of diffuse radiation for the lowland region of Central Europe (Dfb climate zone). In mountainous regions (Dfc climate zone), the estimated *Kdif* values are subject to a larger error than in lowland areas. However, the *ACI*-based method also provides satisfactory results for approximation of diffuse radiation in mountainous regions of Central Europe.

The study suggests also that the proposed *ACI*-based estimation model can be applied to other climate zones (as examined Csa and Aw climate zones). However, it should be noted that the studies conducted in central Mongolia and southern Vietnam covered only short periods in the summer (Mongolia) or spring (Vietnam) seasons. Therefore, further research is needed to cover other seasons.

There is still open the problem of most accurate approximation of atmosphere transparency. The present research underline that atmospheric clearness approach is more credible than turbidity one while *TL* values change both, geographically and seasonally and their exact values are difficult to establish and find in literature.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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