POROVNÁNÍ RŮZNÝCH METOD VÝPOČTU DENNÍ SUMY GLOBÁLNÍ RADIACE

COMPARISON OF VARIOUS METHODS FOR ESTIMATING DAILY GLOBAL SOLAR RADIATION

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ABSTRACT: Seven methods for estimating daily global radiation have been tested on ten sites in the Czech Republic and Austria. The total number of years for which all necessary data were available was 114 i.e. 41 640 observational days. Coefficient of determination, average root mean square error (RMSE) and mean bias error (MBE) values indicated that the highest precision is reached when sunshine duration is used as predictor. For Angstrom's method RMSE value (year mean) equaled 1.6 $MJ.m^{-2}.day^{-1}$ and MBE 0.3 $MJ.m^{-2}.day^{-1}$. Generally the Angstrom's method is superior to all tested methods. If there are no reliable sunshine duration data Supit´s formula yields sufficiently precise outputs if good quality data on nebulosity and daily maximum and minimum air temperature are provided. If nebulosity is not available Winslow's method that replaces nebulosity with daily sum of precipitation should be used. If precipitation is not measured then Donatelli´s method might be applied.

KEY WORDS: global radiation models, Angström-Prescott model, Klabzuba model, Winslow model, Supit model, Donatelli model

INTRODUCTION

Daily global solar radiation (R_G) is required by most models that simulate crop growth because growth is primarily based on the photosynthetic processes, which involve the utilization of radiation and its conversion to chemical energy. Global solar radiation is also indispensable input to most methods for estimating potential and actual evapotranspiration that are part of not only crop growth models but also hydrological models. Records of global solar radiation using instruments such as pyranometers or actinometeres are available, however, majority of meteorological stations in the Central Europe (and all over the world) still does not measure solar radiation. On the contrary all of these stations register other variables such as precipitation, nebulosity, air temperature or sunshine duration hours. In order to use crop growth models (or hydrological models) techniques are required to estimate radiation based on other commonly measured meteorological variables for days or years when the data are missing or for the sites when the data are not measured. Two methods used to generate radiation data are stochastic generation (e.g. Richardson, 1981) and empirical relationships (e.g. Angström, 1924). Stochastic generated data may be useful to explore possible model scenarios for an average theoretical situation of long-term simulation. However the data generated by this approach cannot be used for model validation and simulation analysis for a particular period of time as the method may not generate the data to match the actual weather at particular time of interest (Liu and Scott, 2001).

Using empirical relationships requires the development of set of equations to estimate solar radiation from the commonly measured meteorological variables. A number of formulae have been reported using this approach out of which seven have been tested in this paper.

Daily total extraterrestrial radiation (Q_0) is often included in the relationships. The underlying approach is to express solar radiation reaching earth surface (Q) as fraction of Q_0. This is based on the attenuation of incoming radiation through the atmosphere. The physics involved in the interaction between radiation and atmospheric constituents are complex, but the relationship between atmospheric transmittance and some weather variables can be empirically described. Parameters used as inputs in these relationships include beside others sunshine duration (e.g. Angström, 1924 modified by Prescott, 1940), temperature (e.g. Hargreaves *et al.,* 1985; Donatelli and Campbell, 1998), temperature in combination with nebulosity (Supit and Kappel, 1998) and temperature in combination with daily precipitation sum (Thornton and Running, 1999; Winslow *et al.,* 2001). Availability of weather data at locations varies from only one variable to several variables so models tested in the study should suit varying availability of data. The aim of the study was to evaluate the accuracy and applicability of several models for estimating daily values of solar radiation (Q) across Central Europe for different situations: sunshine duration available, nebulosity and temperature available, temperature and daily precipitation sum available or only temperature available at the particular site. Final outcome of the study should serve as guidance in case of completing missing solar radiation data for various purposes.

MATERIALS AND METHODS

Sunshine duration is the standard and probably the most frequent variable used for estimating daily solar radiation and therefore Angström formula in the form described by Martínez-Lozano *et al.* (1984) was used as the basic reference method. Method of Klabzuba *et al.* (1999) is based on the statistical relationship between relative sunshine duration on a given day and daily solar radiation. It was derived based on long-term observed data from one station (also included in the study) and performs very well during vegetation season. The main advantage of the method (in comparison with the previous one) is applicability without knowledge of site-specific coefficients. As the nebulosity is weather element, which is also measured on large number stations, method proposed by Supit and Kappel (1998) was tested. These authors derived empirical formula including daily maximum and minimum temperature in combination with nebulosity and this method is currently widely applied in the Crop Growth Monitoring System across whole Europe and other parts of the world (Supit, 1997). In many cases neither sunshine duration nor nebulosity are available and thus additional four methods were tested. Methods proposed by Winslow *et al.* (2001) and Thornton and Running (1999) require daily maximum and minimum temperatures and daily sum of precipitation as inputs. The later method is suitable also for estimating hourly sums of solar radiation. In some cases only records on temperature are available and in such case method proposed by Hargreaves *et al.* (1985) is frequently used. In order to compare precision of this well-known formula, the method introduced by Donatelli and Campbell (1998) was also tested. All methods (with exception of formula derived by Klabzuba *et al.*) use daily (or hourly) total extraterrestrial radiation (Q_0). For the purpose of the study the extraterrestrial radiation was calculated by methods published in Allen *et al.* (1998) eq. 21 (daily data) and 28 (hourly data). Solar constant was set at 0.0820 $MJ.m^{-2}.day^{-1}$. Empirical coefficients required by Angström´s, Hargreaves´ and Supit´s methods were estimated from the interpolated maps available at http://home.concepts-ictl.nl/~iwan-supit/radiation (2003).

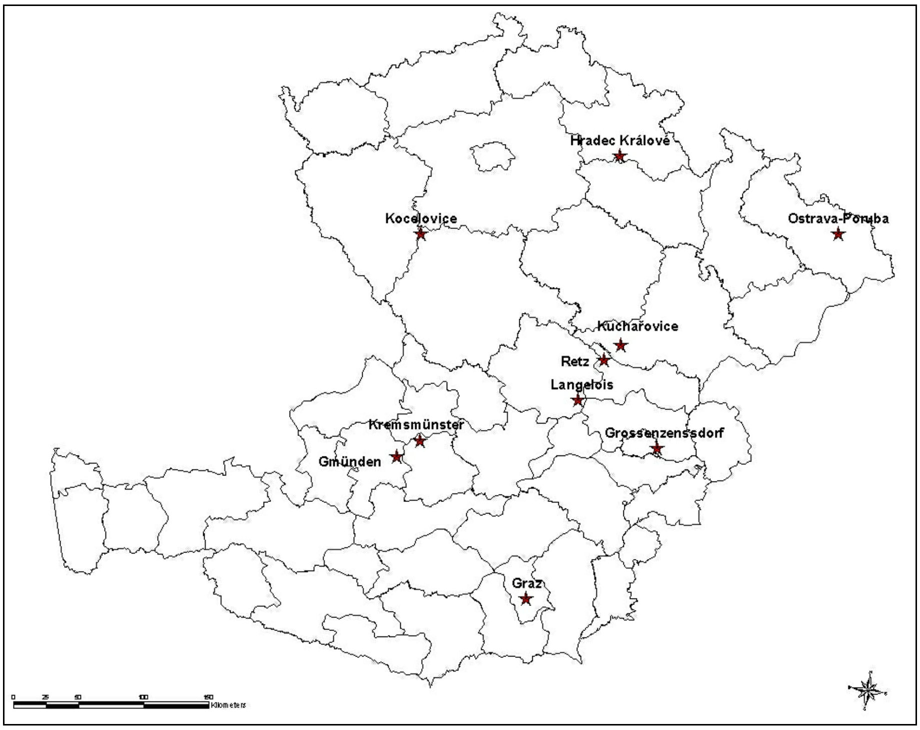

Fig. 1: Map of meteorological stations (solar radiation observatories) used in the study.

Table 1: Overview of meteorological stations (solar radiation observatories) used in the study.

Station no.	Station name	Latitude	Longitude	Altitude	Number of years	Notes
1	Grossenzesdorf	48°12´	16°34´	153 m	6	
2	Gmunden	47°55´	13°55´	426 m	12	
3	Hradec Králové	50°11´	15°50´	285 m	17	
4	Graz	46°58´	15°26	340 m	12	
5	Kocelovice	49°28´	13°50´	519 m	15	
6	Kuchařovice	48°53´	16°05´	334 m	16	
7	Kremsmünster	48°03´	14°08´	383 m	8	No data on nebulosity
8	Langelois	48°28	15°42´	210 m	8	
9	Ostrava-Poruba	49°48´	18°15´	242 m	11	
10	Retz	48°46´	15°55´	242 m	9	No data on nebulosity

Measured meteorological data used as inputs for the individual methods originate from 10 stations located in Austria and Czech Republic, which were selected as the most reliable from total number of 16 stations considered at the beginning of the study. The basic requirement was the availability of measured solar radiation at the site. Stations were then selected according their geographical position (Fig. 1), altitude (Table 1) and also number of complete observational years. As most of the agricultural production takes place in altitudes below 600 m above sea level the study included just the stations within this range. Only those years during which no missing or corrupt data of all necessary parameters were available were used for the calculations and comparisons. In total 114 complete observational years (i.e. 41 640 observational days) were available for the calculations with exception of Supit method where only 97 years (i.e. 35 427 observational days) were available.

After estimating daily global solar radiation values the results were compared with observed values. To assess the predictive accuracy for daily radiation estimates the root mean square error (RMSE) and the mean bias error (MBE) were calculated. The RMSE is calculated as:

$$\text{RMSE} = \sqrt{\frac{\sum (Q_{observed} - Q_{estimated})^2}{N_{observed}}}$$

Where $Q_{observed}$ and $Q_{estimated}$ substitutes observed and estimated global radiation values (MJ.m^{-2}.day^{-1}) and $N_{observed}$ is the number of observations. The MBE is calculated as:

$$\text{MBE} = \frac{\sum (Q_{observed} - Q_{estimated})}{N_{observed}}$$

In order to illustrate relationship between the observed and calculated values of coefficient of determination and slope of the regression line (forced through origin) were provided for whole year and also for "cold" (October-December&January-March) and "warm" (April-September) months.

RESULTS

Table 1 presents the regression statistics. The average coefficient of determination r^2 is highest for the methods based on the sunshine duration followed by results of Supit method based on combination of temperature values with nebulosity. These methods show r^2 value for whole year higher than 0.90 with slope of regression line forced through origin close to the unity. The remaining four methods could be put in the following order based on the explained variability: Winslow's method, Donatelli´s method Thornton's method and Hargreaves´ method. As it is clear from the Fig. 2 the deviation between observed and estimated Q values increase significantly when other predictors than sunshine duration are used. However even with the use of temperature and precipitation as inputs for global solar radiation estimate satisfactory overall results might be expected if Winslow's method is applied.
Generally MBE values are in the range from 0.94 to 1.78 (MJ.m^{-2}.day^{-1}) depending on the method and year with highest deviation for Klabzuba´s . method from September to March. Relative MBE figures are lowest from May to July and highest for December and January. This is caused by low values of incoming solar radiation hence small error in the estimate leads to high relative error. RMSE (Fig. 3) show significant annual pattern with absolute RMSE values reaching maximum during summer months (relative RMSE show opposite trend due to the same reason as relative MBE). RMSE for Angstrom's method (based on average from 10 stations) is smaller than 2.33 (MJ.m^{-2}.day^{-1}) with relative RMSE in range 10.7-31.8%. RMSE for Supit method is within 0.85-3.38 (MJ.m^{-2}.day^{-1}) with relative RMSE between 19.2 and 43.7%, while the same parameters for Winslow method are 1.26-4.55 (MJ.m^{-2}.day^{-1}) and 20.6-50.3% respectively. While there are no significant differences between individual sites in relative RMSE (Fig. 4) there is clear difference in site-specific MBE values. The lowest annual MBE was recorded at Kocelovice and Kuchařovice while the highest deviations (regardless method applied) was found for Ostrava-Poruba.

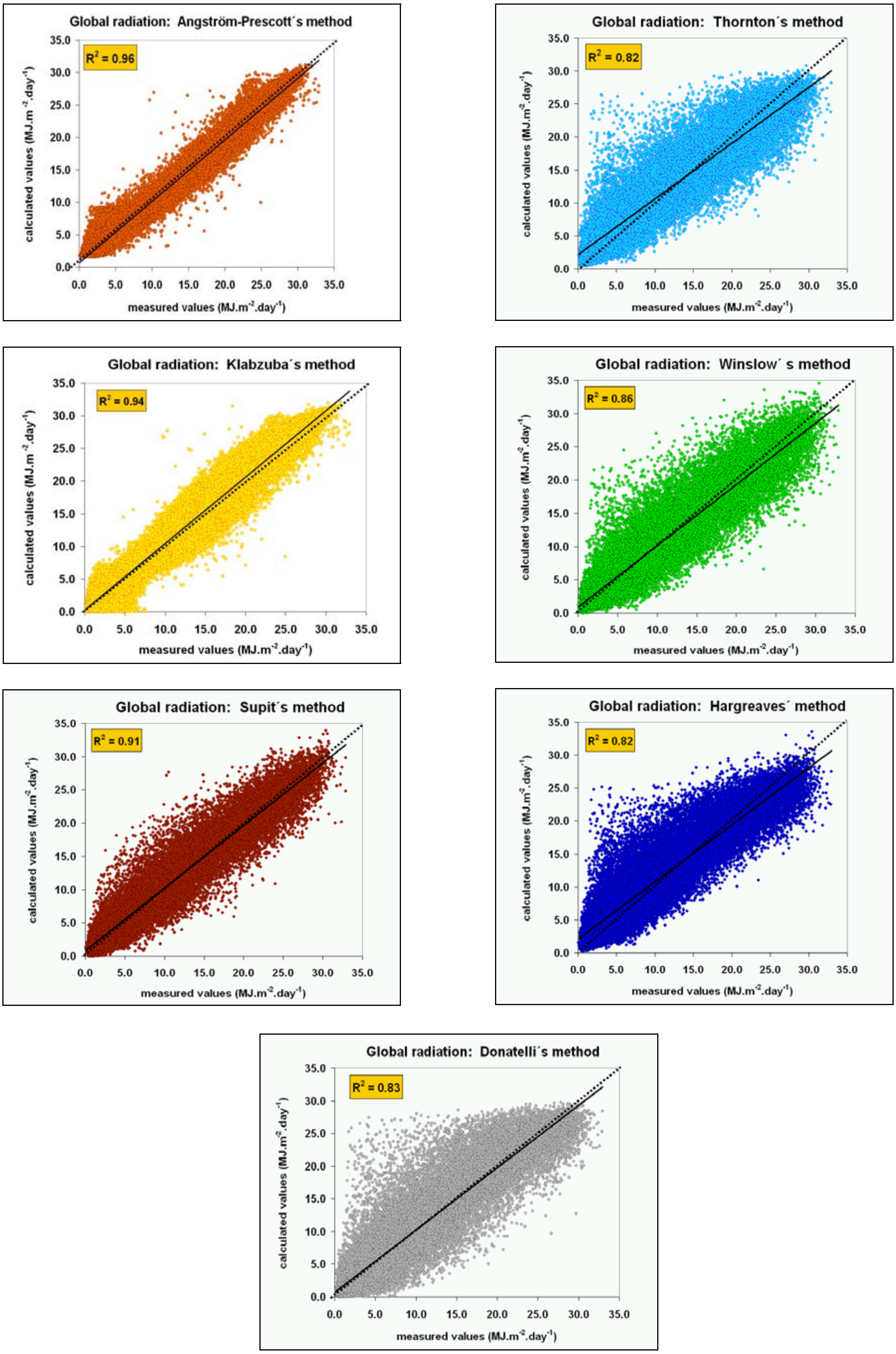

Fig. 2. Scatter plot charts presenting relationship between estimated and observed value of daily global solar radiation. Data from all 10 (8 in case of Supit´s method) are pooled together (n = 41 640 observational days). Dotted line represents 1:1line while solid line represents linear regression not forced through 0.

Table 2: Overall performance of each method is expressed in terms of slope of linear regression line forced through the origin (0) and variability explained by such a line. Additionally coefficient of determination for plain linear regression line* is given.

Month	Method						
	Angström	*Klabzuba*	*Supit**	*Thornton*	*Winslow*	*Hargreaves*	*Donatelli*
Whole year							
Slope of regression line	0.99	1.03	0.99	0.97	0.97	0.99	0.99
R^2	0.96	0.93	0.90	0.79	0.85	0.79	0.83
$*R^2$	0.96	0.94	0.91	0.82	0.86	0.82	0.83
Warm half year (April-September)							
Slope of regression line	0.99	1.03	0.99	0.97	1.00	1.01	1.02
R^2	0.91	0.89	0.76	0.51	0.62	0.23	0.56
$*R^2$	0.92	0.89	0.80	0.66	0.71	0.64	0.66
Cold half year (January-March & October-December)							
Slope of regression line	0.98	1.10	0.96	0.97	0.86	0.90	0.85
R^2	0.91	0.93	0.83	0.60	0.70	0.62	0.68
$*R^2$	0.92	0.93	0.83	0.67	0.72	0.68	0.68

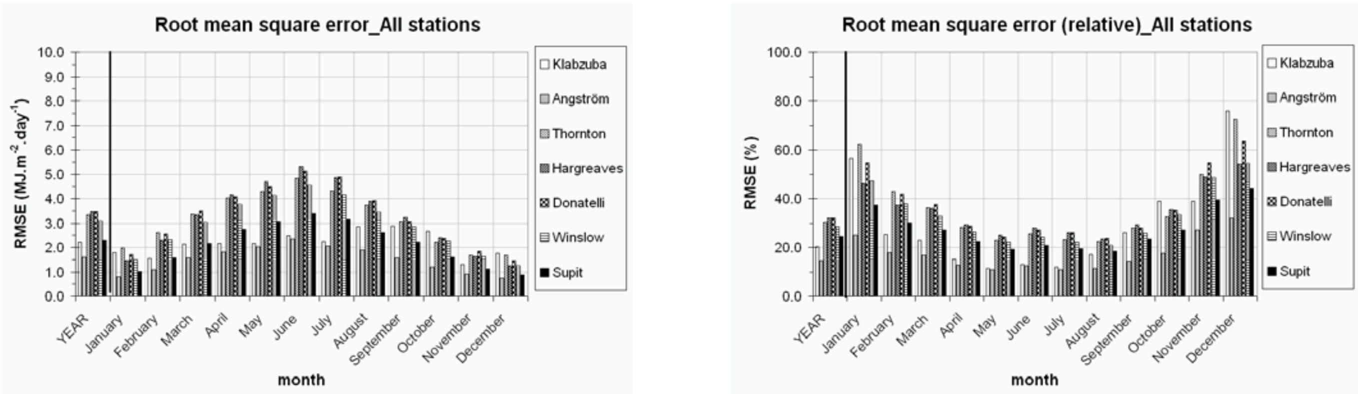

Fig. 3. Values of root mean square error (RMSE) calculated for individual methods and pooled together for all sites used in the study.

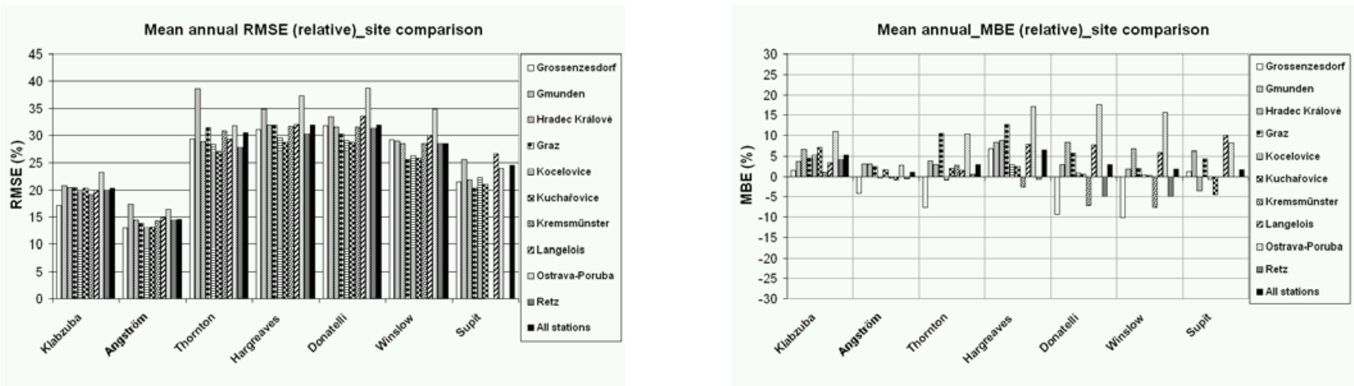

Fig. 4. Values RMSE and MBE (annual mean) calculated for individual methods and pooled together for all 10 sites used in the study.

The final outcome of the study is presented on the Fig. 5. which might serve as basic guide for selecting proper method for calculating missing daily values of global solar radiation. In the same time the flowing chart indicates error of each method used for estimating daily values of solar radiation in the conditions of the Central Europe. It should be noted that these results could be achieved without any further calibration of any method i.e. just based on the already available method coefficient and constants.

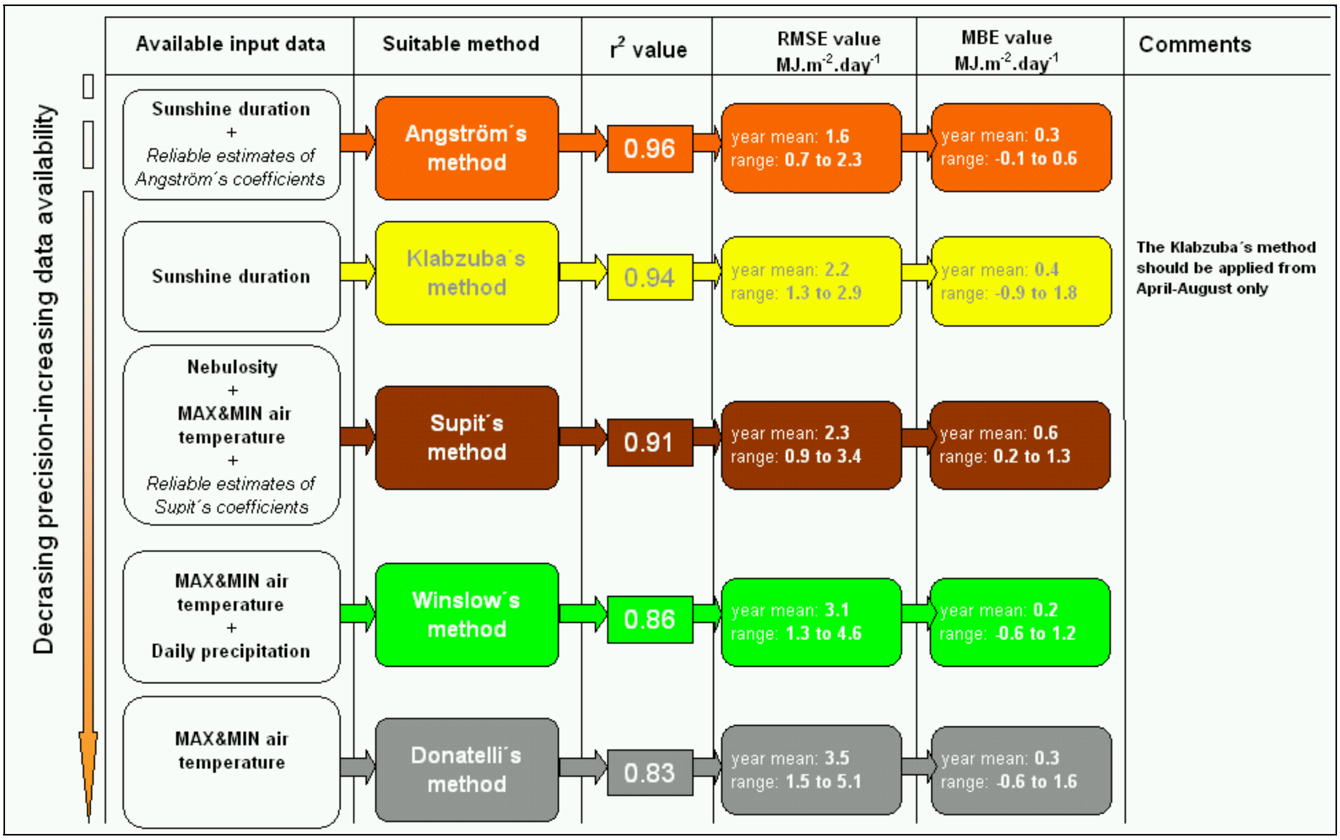

Fig. 5. Flowing chart should serve for selecting proper method for estimating daily values of global solar radiation (if there is no direct measurement) based on the available data. Basic parameters of estimate precision for each method are given.

CONCLUSIONS

Seven methods for estimating daily global radiation have been tested. Average regression coefficient, RMSE and MBE values indicated that the highest precision is reached when sunshine duration is used as predictor. For Angstrom's method RMSE value (year mean) is 1.6 $MJ.m^{-2}.day^{-1}$ and MBE 0.3 $MJ.m^{-2}.day^{-1}$. Generally the Angstrom's method is superior to all tested methods. If there are no reliable estimates of coefficients necessary for Angström method Klabzuba methods can be used for period from April to August. In the other months the error increases greatly. If there are no reliable sunshine duration data Supit formula yields sufficiently precise outputs providing good quality data on nebulosity and daily maximum and minimum air temperature. If nebulosity observations are not available Winslow's method that replaces nebulosity with daily sum of precipitation should be used instead. If precipitation is not measured then Donatelli method might be applied.

SOUHRN: Studie se zabývá porovnáním sedmi různých metod výpočtu globální radiace na deseti vybraných lokalitách v České republice a v Rakousku. Celkový počet let, pro která byla dostupná kompletní data, byl 114 tj. 41 640 dní. Hodnoty regresních koeficientů, střední kvadratické chyby a průměrné odchylky ukázaly, že nejlepších výsledků je dosaženo při použití doby slunečního svitu jako prediktoru. Pro Angströmovu metodu je hodnota RMSE (roční průměr) 1.6 $MJ.m^{-2}.den^{-1}$ a MBE 0.3 $MJ.m^{-2}.den^{-1}$. Angströmova metoda je jednoznačně nejpřesnější metodou

ze všech metod hodnocených v rámci studie. V případě, že nejsou k dispozici spolehlivé údaje o době slunečního svitu je vhodné použít metodu Supitovu, která jako vstupy využívá hodnoty oblačnosti, maximální a minimální teploty. V případě, že údaje o oblačnosti nejsou na stanici měřena je možné využít metodu Winslowovu, jež namísto oblačnosti používá jako prediktor denní úhrn srážek (v kombinaci s denními extrémy teplot). A konečně pokud jsou k dispozici pouze údaje o maximální a minimální teplotě jeví se Donatelliho metoda jako nejlepší alternativa.

KLÍČOVÁ SLOVA: modely globální radiace, Angström-Prescottova metoda, Klabzubova metoda, Winslowova metoda, Supitova metoda, Donatelliho metoda

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