A locally adaptable clear sky model for calibration of global radiation data from field pyranometers

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The continuous development of advanced simulation tools has facilitated detailed building performance assessment. The quality and accuracy of the results is very sensitive to the quality of the climate data at the building site, in particular for buildings that are naturally ventilated and/or use passive solar features. Test reference or design reference years (TRY/DRY) are commonly used, and such data records are available for some sites. However, due to different climatic patterns, solar radiation can vary significantly even at closely located sites. It is therefore a need for more locally derived data.

In Norway there are currently 545 weather stations. Many of these are equipped with pyranometers, and hourly data records are available. Pyranometers measure the global (total) solar radiation coming from the sky. These data can be used to generate complete solar radiation data for building simulation through the application of a diffuse fraction model with adequate level of accuracy.

However, the pyranometers placed in the field vary in quality, and many of them are not calibrated very often. Based on the work of Psiloglou, Santamouris and Asimakopoulos [1] it has been demonstrated how a clear sky model for prediction of beam and diffuse radiation can be adapted to local or regional climatic conditions through modifications of the total aerosol broadband transmission function and the absorption broadband transmission function. The model can be tuned if measured beam radiation data for clear days are available. When tuned, the model will give good estimates for the global radiation, which can be used as an alternative method to calibrate data from pyranometers.

This technique has been demonstrated by using reliable data from Trondheim, Norway, measured by two calibrated pyrheliometers mounted on a solar tracker (pyrheliometers measure the direct-beam solar radiation). The result is a clear sky model tuned for regional conditions in Trondheim. If atmospheric conditions are similar to that of the region of Trondheim, this tuned model can be used as a rough method to calibrate pyranometers for other locations without access to other radiation data. The inputs needed are measured global radiation, time, solar position, temperature and humidity data for a selection of clear days.

The method is validated by comparing the measured beam radiation with the predicted beam radiation when applying the diffuse fraction model of Skartveit, Olseth and Tuft [2] with calibrated global radiation data as input.

1 Background theory

Models for prediction of the solar position are taken from Clarke [3]. The models are based on a number of texts, and the accuracy is commensurate with our requirements. However, models that are more accurate can be found elsewhere [4]. If very high tracking accuracy of the solar position is needed, other newly developed algorithms are recommended, e.g. the PSA algorithm [5]. The source code (C++) of the PSA algorithm is made available at http://www.psa.es/sdg/sunpos.htm.

The intensity of extraterrestrial solar radiation, with transformation to the extraterrestrial horizontal plane is given by [6]:

$$I_E = 1353\left[1 + 0{,}033\cos(0.0172024Y)\right]\sin\beta_s \qquad (1)$$

Y is the day number of the year (Jan. 1=1, Feb. 1=32 etc.) and β_s is the solar altitude.

When solar radiation enters the earth's atmosphere, a part of the incident energy is lost by the mechanisms of scattering and absorption. The scattered radiation is called diffuse radiation, while the part that arrives at the surface of the earth directly from the sun is called direct or beam radiation. The attenuation of light through a medium is related to the distance traversed in the medium and the local radiation flux [7]:

$$I_B = I_E \exp(-km) \qquad (2)$$

Here, m is the air mass defined as the path length traversed by a solar ray, multiplied by the density of the molecules, and given by [8]:

$$m = \left[\sin(\beta_s) + 0.50572(\beta_s + 6.07995)^{-1.6364}\right]^{-1} \cdot (p/1013.25) \qquad (3)$$

This equation is applicable with 99.6% accuracy to a standard pressure of 1013.25 mbar, and $(p/1013.25)$ is a correction factor for variations in this pressure. An approximate value for this factor as a function of the height above sea level, can be calculated by [9]:

$$(p/1013.25) = \exp(-0.0001184h) \qquad (4)$$

The transmittance can be defined as $\tau = \exp(-km)$, where k is known as the total attenuation coefficient. When an electromagnetic wave strikes a particle, the energy is scattered in all directions. Different transmittance factors can be defined for the different kinds of scattering. If scattered by particles smaller than a wavelength, this is called Rayleigh scattering with transmittance τ_r, and if in the order of one wavelength, Mie scattering with transmittance τ_α. Air molecules cause Rayleigh and aerosol Mie scattering. In addition, we define transmittances for mixed gas, ozone and water as τ_g, τ_{oz}

and τ_w. By introducing *SF* as the hourly sunshine fraction attenuating the beam radiation in cases where the sky is not clear (*SF*=1 if clear, and 0 if fully overcast sky), the beam radiation can be expressed as [7]:

$$I_{Ba} = SF \cdot I_B = SF \cdot I_E \tau = SF \cdot I_E \tau_r \tau_g \tau_\alpha \tau_w \tau_{oz} \qquad (5)$$

where the index *a* stands for "all sky", and I_B is the beam radiation on a truly clear day defined in Equation (2).

2 Development of an adaptable clear sky model

Various models exist for the different transmittances. In this work, we started with models proposed by Muneer et. al. [10] who uses Davies et al's model [11] for the Rayleigh transmittance. However, it was found that this model clearly gives unrealistic estimates when the solar altitude is low. The transmittance function, τ, actually increases with the air mass (*m)* when *m*>5.75 and becomes higher than one when *m*>12. Thus, it should not be used for solar elevations lower than 15^0.

This can also be seen from the work of Psiloglou et. al. [12] where several models for broadband Rayleigh scattering are compared, and a new model developed. Psiloglou et. al. compared their models with measured data, and found very good agreement [1]. By use of parameterisation techniques, they obtained the following analytical expression for the Rayleigh transmittance function:

$$\tau_r = \exp\left[-A_1 \cdot m^{A_2} (A_3 - m^{A_4} + A_5 m)\right] \qquad (6)$$

where A_1=0.112768, A_2=0.112768 A_3=0.112768 A_4=0.112768 and A_5=0.112768, and m is defined in Equation (3) above.

The mixed gas transmittance is given by [13]

$$\tau_g = \exp\left[-COF(13) m^{COF(14)}\right] \qquad (7)$$

where *COF(13)* equals 0.01235, 0.01318 or 0.0123 while *COF(14)* equals 0.25781, 0.26815 or 0.25380 for clear, overcast and partly overcast conditions respectively.

The aerosol Mie scattering transmittance depends strongly on the concentration of aerosol particles in the atmosphere. Variations in the free tropospheric layer as well as the stratospheric level are relatively independent of local environmental conditions. However, surface layer aerosols (0-3 km) are strongly dependent on man made sources at the Earth's surface, as well as on local environmental and climatic conditions. Water-soluble particles (especially sulphates), dust particles picked up from the Earths surface and carbonaceous- and sea-salt particles are the most important elements. Based on an analysis of these factors, Psiloglou et. al. [1] define a total extinction (ext)- and absorption (abs) aerosol broadband transmission function:

$$\tau_\alpha(ext) = 1 - \frac{B_1 \cdot m}{((1+B_2 \cdot m)^{B_3} + B_4 \cdot m)} \qquad (8)$$

B1=0.2579*, B2*=0.04*, B3*=-2.8451*, B4*=0.2748

$$\tau_\alpha(abs) = C_0 + C_1 \cdot m + C_2 \cdot m^2 + C_3 \cdot m^3 \qquad (9)$$

C_0=1.0001, C_1=-1.41·10^3, C_2=-9.013·10^{-5}, C_3=2.2·10^{-6}

Only Equation (8) will have influence on the beam radiation, while the diffuse component also depends on the absorption effect of the aerosols represented in Equation (9). However, these two functions were developed to predict the aerosol extinction over a medium large coastal or near coastal city with important emission of combustion products from industrial anthropogenic sources, in a Mediterranean climate (Athens). They can therefore not be expected to perform well for conditions in Trondheim. It was therefore attempted to tune the model through the introduction of an aerosol reduction factor, $0<\alpha_{red}<1$:

$$\tau_\alpha(ext) = 1 - \frac{B_1 \cdot m}{((1+B_2 \cdot m)^{B_3} + B_4 \cdot m)} \cdot (1-\alpha_{red}) \qquad (10)$$

$$\tau_\alpha(abs) = \alpha_{red} + (C_0 + C_1 \cdot m + C_2 \cdot m^2 + C_3 \cdot m^3) \cdot (1-\alpha_{red}) \qquad (11)$$

A function describing the effect of scattering (sct) as well as a modification of the water vapour and ozone transmittance are given by the model of Psiloglou et. al [1]:

$$\tau_\alpha(sct) = \frac{\tau_\alpha(ext)}{\tau_\alpha(abs)} \qquad (12)$$

$$\tau_w = 1 - \frac{3.014 \cdot l_w \cdot m}{((1+119.3 \cdot l_w \cdot m)^{0.644} + 5.814 \cdot l_w \cdot m)} \qquad (13)$$

$$\tau_{oz} = \frac{0.25537 \cdot l_{oz} \cdot m}{((1+6107.26 \cdot l_{oz} \cdot m)^{0.204} + 0.4707 \cdot l_{oz} \cdot m)} \qquad (14)$$

where l_{oz} is the total amount of ozone in a vertical column of the atmosphere, either measured [14] or as in our case, predicted by Van Heuklon's formula [15]. l_w is the amount of water vapour in the entire depth of the atmosphere (referred to as precipitable water) estimated via radiosonde data or, as in our case, predicted through use of the following correlation [16]:

$$l_w = \exp(0.07 \cdot DPT - 0.075) \qquad (15)$$

DPT is the dew point temperature, obtained from the given dry and wet bulb temperatures, or temperature and humidity data. In the present case, temperature and humidity are known, and *DPT* is calculated through the application of the empirically derived algorithm developed for the Advanced Weather Interactive Processing System (AWIPS) [17].

The beam radiation is now estimated by Equation (5) with $\tau_{\alpha}(ext)$ from Equation (10) replacing τ_{α}. However, the model first requires tuning of the aerosol reduction factor (α_{red}). This factor is initially set to zero, reflecting the original model.

The diffuse radiation is given by [1]:

$$I_D = I_{D1} + I_{D2} \tag{16}$$

where

$$I_{D1} = \frac{I_E \tau_g \tau_{oz} \tau_w \tau_{\alpha}(abs) \cdot (1 - \tau_{\alpha}(sct) \cdot \tau_r)}{2} \tag{17}$$

$$I_{D2} = (I_B + I_{D1}) \frac{r_g \cdot r_{cs}}{1 - r_g \cdot r_{cs}} \tag{18}$$

Here, r_g is the ground albedo (set to 0.15) and r_{cs} is the albedo of the cloudless sky, given by the following equation [13,18]:

$$r_{cs} = 0.0685 + 0.17(1 - \tau_{cs}) \tag{19}$$

τ_{cs} is the Rayleigh scattering transmittance given by Equation (6) computed with m=1.66.

The global (total) radiation can now be expressed simply as:

$$I_G = I_D + I_B \tag{20}$$

α_{red} is now found by requiring that the predicted maximum beam radiation must equal the maximum beam radiation.

Note also that for fully overcast skies (*SF=0*), there will be no beam component, and I_G can easily be found by setting I_B.=0 in Equation (20).

3 All sky conditions

The above theory enables estimation of the global and diffuse irradiation on a horizontal surface for cloudless and fully overcast skies. Such conditions are the easiest to deal with. On the other hand, situations with partly covered skies can be extremely complex. Clouds can change the diffuse fraction by affecting the diffuse and beam irradiance in multiple ways. In some cases, the global radiation can even be higher on a partly cloudy than on a clear day due to reflections from clouds not obstructing the sun.

If the sunshine fraction (*SF*) is known, the beam radiation can be calculated from Equation (5). However, the sunshine fraction is not often measured. Actually, pyranometers measuring global radiation is the most common instrument at weather stations logging solar radiation data. This establishes a need for so-called *diffuse fraction models*, which are models and algorithms predicting the diffuse and direct component from the measured global radiation.

Global radiation data mostly consist of hourly mean values. A number of diffuse fraction models are available that can be used on these data. A model with correction for variability and ground albedo developed by Skartveit, Olseth and Tuft [2] has been chosen for the present analysis. The model consists of base-correlation to which a correction term is added in order to take the variability in the cloud cover into account.

The model is tuned by least squares analysis to 32 years of data from Bergen (60.4^{0}N; 5.32^{0}E), Norway (1965-1996, 77479 hours) for the months April-October, during which period a regional snow free surface albedo of 0.15 is a realistic estimate. Testing and comparison with other selected diffuse fraction models, i.e. Erbs' [19] , Maxwell's [20] and Perez' [21] were made against comprehensive sets of experimental data from Bergen, Garston (U.K.), Lisbon (Portugal), Lyon (France) and Gävle (Sweden). The model of Skartveit et al. showed best overall performance, and very good results are reported.

4 Model implementation

All models presented above, including the empirical model of Skartveit, Olseth and Tuft [22] have been implemented into a program named "Solrad" written in the Fortran programming language. The program was used to compare the theoretical models introduced above with measured data (minute values) from Trondheim (63.590N, 10.380E) in Norway. All data are measured about 50 m above mean sea level. Results are also compared with the work of I. Brevik [23], who measured and analysed nearly complete sets of radiation data from summer 1981 to summer 1983 in Trondheim (Lade).

For each minute, the program reads the mean radiation data from the minute records 1.5 hours before and after the actual time-step. This enables the calculation of the mean values for the preceding, the current, and the following hour, as well as analysing variations within each of these three hours. Although a significant amount of code is necessary, implementation of the different models was relatively straightforward.

5 Comparison with data from clear sky conditions

Clear days provide the easiest conditions to consider and are thus vital for testing and eventually calibrating measurement equipment. In addition, such days are very important to consider when designing buildings and especially buildings that uses passive technologies i.e. naturally ventilated buildings and buildings with atria, double skin facades, daylight systems, solar thermal collectors or photovoltaic cells. Finally, investigating such days can give vital information regarding local or regional atmospheric conditions.

In order to find out how the above described models work when influence from clouds is minimal, testing has been done against data sets from clear days in Trondheim. The current test site is situated at the roof of one of the buildings (Realfagsbygget) at the Norwegian University of Science and Technology, Trondheim. The direct beam radiation is measured using two calibrated pyrheliometers at normal incidence to the sun, with radiometer calibration traceable to the World Radiometric Reference (WRR). Two Eppley pyranometers measures the global radiation at a horizontal surface. The well-recognised method developed by Forgan [24] was used in order to calibrate them against each other. It was found that values from the newest pyranometer (from 2000) on the average were as much as 1.1604 times higher that values from the old one (from 1977).

Data from the current test site has been generated since may 2000. Values are sampled every second, and mean values and corresponding standard deviations are calculated and recorded for each minute. Data records from the period July-October 2002 are used in the present analysis.

The ground albedo is assumed 0.15 at the test-site for the months July-September, and 0.2 in October. This is based on the fact that the ground is relatively densely covered with broad-leaved forest (mainly birch), and that the leaves changed colour from green to yellow around the end of September. Temperature and humidity data needed for calculating the water vapour transmittance were obtained from *The Norwegian Crop Research Institute's* agro-meteorological station at Frosta (63.56^{0}N, 10.69^{0}E) situated to the north east of Trondheim, approximately 30 kilometres away.

The diffuse radiation is deduced from the measurements by transforming the beam radiation to the horizontal plane and subtracting this value from the measured global radiation. Even though not measured directly, this value will in the following be referred to as the measured diffuse radiation. These measurements were first compared with the clear sky model presented above, calculating the global radiation from Equation (20), the diffuse radiation from Equation (16), and the beam radiation from Equation (5).

For all the clear days considered, the predicted global radiation turned out to be considerably lower than the measured value. This was expected since the aerosol reduction coefficient, α_{red}, initially was set to zero, see Equation (10). Recall that the expression for the aerosol transmittance originally was tuned for coastal cities in Greece.

It was first attempted to tune the clear sky model by increasing α_{red} until the predicted global radiation matched the measurements. However, it turned out that the diffuse to global ratio from the clear sky model was considerably higher than the measured value for all days. The correctness of the measured value was therefore questioned, and comparison with comprehensive datasets from the work of Brevik [23] clearly indicated that the diffuse radiation deduced from the measured global radiation was too low. It was thus clear that calibration of also the pyranometers was needed.

By tuning the modified clear sky model so that the predicted beam radiance matches the maximum measured values close to noon, an aerosol reduction coefficient α_{red} is obtained for each of these days. Further, a *calibration factor* is obtained by requiring that the measured global radiation must match the global radiation predicted by the clear sky model. This introduces a new method to calibrate a pyranometer based on reliable measured beam radiation data. The results are shown in Table 5-1.

The aerosol reduction factor varies between 53% and 89%. We thus argue that using a mean value of 67% in our modified clear sky model would give realistic estimates for the region of Trondheim. The predicted calibration factor varies between 1.049 and 1.92, with 1.08 as an average value. October 9 represent the worst case, the measured global radiation differing 3% from the calibrated value. On this day the maximum measured global radiation is around 300 W/m^2, for which 3% amount to 9W/m^2. This is within the accuracy of the pyranometers, given to be $\pm$ 10W/m^2 (note that this accuracy is only valid for a perfectly calibrated pyranometer with perfect positioning of the radiation sensor).

The measured global radiation has also been compared with values from the pyranometer at the agro meteorological station at Frosta (63.56^{0}N, 10.69^{0}E), as well as with the meteorological station at Voll, Trondheim. The Norwegian Crop Research Institute and the Norwegian Meteorological Institute own the meteorological stations respectively. For the selected days, global radiation data from the pyranometer at Frosta are 1-11% higher, while the data from Voll are 2-5% higher than our measured data. Even though the calibration routines for these stations are not known in detail, they still give an indication that the proposed calibration of the pyranometers used in this analysis is in place.

A calibration factor of 1.08 was therefore introduced for the newer of the two pyranometers, while the calibration factor for the older is set to 1.08·1.1604=1.2532.

Table 5-1 Results from analysis of clear days in Trondheim 1 July-15 October 2002.

Day	β_{Smax}	Relative humidity	Temperature	α_{red}	Calibration factor
21 July	46.85 0	30-83 %	10-23 0C	70 %	1.088
2 August	44.06 0	43-86 %	9-25 0C	72 %	1.086
3 August	43.79 0	30-78 %	13-26 0C	53 %	1.088
4 August	43.52 0	36-74 %	13-22 0C	73 %	1.092
22 August	37.82 0	60-86 %	16-23 0C	55 %	1.073
24 August	37.10 0	31-91 %	15-28 0C	57 %	1.083
9 October	19.07 0	50-75 %	1-8 0C	89 %	1.049
Mean value:				67 %	1.080

6 Validation

The introduction of the calibration factor was based on data from a few clear days. It therefore remains to validate the calibrated global radiation data from the pyranometers for random sky conditions.

40 days in the period from July to October 2003 were selected for this validation. The days are selected systematically as the three days following inspection and eventual alignment and levelling of the pyrheliometers and pyranometers. Exception is made for July 20 and 21, as well as for August 23 and 24 (four and five days after last inspection in both cases) since measurements from the 21 of July and 21 of August respectively (clear days) indicate that the pyrheliometer still was well aligned. Perfect accordance between the two pyrheliometers (measuring beam radiation) was observed at all times (57600 minute mean values). We are thus certain about the accuracy of the measured beam radiation.

Global radiation data records from the two calibrated pyranometers were first compared, and showed very good agreement. Having carried out this check, the records from the newer one was now chosen as input for prediction of the beam and diffuse component.
The model of Skartveit et. al. [2] was used for this purpose. Recall that the model originally was tuned by least squares analysis to data from Bergen (1965-1996, 77,479 hours). If it can be assumed that it performs very well also for conditions in Trondheim, the results will indicate whether the calibrated records from the pyranometer are correct by comparing the predicted beam and diffuse radiation with the measurements.

It was observed that for all these days except the 9 October, which was extremely clear (known from visual observations), the predicted beam and diffuse component come very close to the measured values. For the clear days in October, the beam radiation seemed to be somewhat higher than the value predicted by the modified clear sky model. As seen from Table 5-1, increasing α_{red} to 89% would give perfect match for the October 9. Thus, the depletion of solar radiation caused by the various atmospheric components is significantly lower for these days than observed for any of the summer days.

The daily load of diffuse radiation on a horizontal surface and the daily load of beam radiation on a surface in normal incidence to the sun, was compared by integrating the diffuse and beam radiation for each day with respect to time. The results are presented in Table 6-1.

From the results it can also be seen that the model of Skartveit et. al. [2] matches the calibrated data very well. While the total measured diffuse radiation energy load on a horizontal surface for all days is 63.65 KWh/m^2, the model of Skartveit et. al. gives 64.01 kWh/m^2. Likewise, the total measured direct radiation energy load on a surface perpendicular to the sun sums up to 162.53 kWh/m^2, while the model of Skartveit et. al. predict 158.98 kWh/m^2. The mean bias deviations are thus 0.006 and -0.02 for the diffuse and beam radiation respectively.

Table 6-1 Comparing the measured and predicted load of diffuse radiation on a horizontal surface, and the beam radiation on a surface in normal incidence to the position of the sun. 40 days in the period July-October 2002 were analysed The values are given in [kWh/m^2]. Predictions are carried out using the model of Skartveit et. al. [2] with the calibrated global radiation data as input. The average error [%] is taken as the sum of absolute errors divided by the total load for all selected days.

	I_D meas.	I_D pred.	I_{Bdir} meas.	I_{Bdir} pred.
Total load [kWh/m^2] for all selected days:	63.65	64.01	162.50	159.00
Average for all selected days:	1.59	1.60	4.06	3.97
Sum of absolute errors for all selected days:	-	6.47	-	16.51
Average error [%]:	-	10.17	-	10.16

7 Conclusions

Models for estimating the effects of radiation under various conditions have been analysed. From the work of Psiloglou et al. [1] a clear sky model has been adapted to regional conditions in Trondheim. Modification was done with respect to the aerosol broadband transmission- and the absorption aerosol broadband transmission function based on the assumption that the levels of atmospheric aerosols are significantly lower in Norway than in Greece, for which the original model was validated and where they cause the most important depletion of solar radiation under clear sky conditions.

This modified clear sky model can be tuned if measured beam radiation data for clear days are available. The model will then give good estimates for the global radiation, which can be used to calibrate pyranometers if no other methods are available. This technique has been demonstrated by using reliable data from Trondheim measured by two perfectly calibrated pyrheliometers mounted on a solar tracker. This result in a clear sky model tuned for regional conditions in Trondheim.

If atmospheric conditions are similar to that of the region of Trondheim, this tuned model can be used as a rough method to calibrate pyranometers on other locations without access to other radiation data. The only inputs needed are measured global radiation, time, position, temperature and humidity data for a selection of clear days. The selected set of clear days should be in summer, and the measured global radiation at the highest elevations should then be calibrated to match the predicted global radiation for the clearest days.

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