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General Formulation of Ångström-Prescott Coefficients: A New Approach for Côte d'Ivoire

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Abstract In this study, we used calibrated annual Ångström-Prescott (AP) coefficients of nine (9) weather stations in Côte d'Ivoire to formalize two general equations expressing them as a function of the latitude and altitude. The aim is formalizing the general equations of Ångström-Prescott coefficients that can be used to increase the density of global horizontal irradiance. The Ångström-Prescott coefficients thus obtained were compared with the values calibrated using the root mean square error (RMSE), the mean bias error (MBE), the mean absolute bias error (MABE), the NSE coefficient and the statistical t-test (t-stat) with the following results for coefficients *a* and *b* respectively: 0.00935143, -0.00042828, 0.00825164, 0.99734601, 0.12129825 and 0.00633772, -0.00017254, 0.00471422, 0.7653197, 0.072056623. To improve the estimation of coefficient *a*, we linked it to the coefficient *b* by a polynomial function of degree two. This equation led to a significant decrease in the absolute estimation error of coefficient *a* resulting in low values of RMSE and MABE. RMSE decreased from 0.00935143 to 0.00498464 and MABE decreased from 0.00825164 to 0.00346367. The low values of the statistical t-test (t-stat) (0.45735957 for *a* and 0.07205623 for *b*) for the two equations show that the model agrees well with the data. The good agreement between the annual Angström-Prescott coefficients estimated and calibrated also confirmed by high NSE coefficients (0.99924593 for *a* and 0.7653197 for *b*) recommends the use of this model in any site in Côte d'Ivoire to predict global horizontal irradiance.

Keywords: *Ångström-Prescott coefficients, global solar radiation, relative sunshine duration, clearness index, statistical t-test*

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1. Introduction

Solar data is useful in the sizing, simulation, performance study and optimization of solar systems.

The aim of the study is to formalize the equations that can be used to increase the availability of solar radiation data using Ångström-Prescott model, sunshine duration data are used as inputs.

The availability of solar radiation data is problematic in some countries with regard to the costs of acquiring and maintaining measurement equipment. To get around this lack, several models have been developed by scientists to estimate global solar irradiation. The simplest Ångström-Prescott model is used to estimate global horizontal irradiance using sunshine duration data as a input. In areas where no measurement of sunshine duration data exists, determination of global horizontal irradiance using Ångström-Prescott coefficients is not possible. To overcome this difficulty, certain considerations have been made. It was first a question of researching the factors which influence the Ångström-Prescott coefficients, then of studying them and finally of correlating them analytically with these factors. The factors that impact Ångström-Prescott coefficients without any order of priority are as follows [1]: the latitude of the place, the altitude of the site, the reflection coefficient of the receiving surface, the average height of the sun, the concentration of water vapor and the atmospheric pollution. The dependence of Ångström-Prescott coefficients on latitude was studied by Glover and McCulloch [3] in 1958. They concluded that the calibrated coefficient *b* is practically constant. The calibrated coefficient *a*, on the other hand, varies with latitude. Driedger [4] in 1970 showed that Ångström-Prescott coefficients evolve in a polynomial function of degree two depending on the day of the year. Sfeir [5] in 1981 also showed that the Ångström-Prescott coefficient *a* is a sinusoidal function of the day of the year. Neuwirth [6] in 1980 came to the conclusion that the Ångström-Prescott coefficients are polynomial functions of order two of the altitude of the stations. Unfortunately the work of Crivelli [7] in 1973 had already contradicted Neuwirth's results. Glover and McCulloch [8] in 1958 suggested a linear relationship between the sum of the Ångström-Prescott coefficients and the optical air mass. Frère et al. [9] in 1975 showed that Ångström-Prescott coefficients are correlated with the mean relative sunshine duration by a quadratic function. Inspired by this idea, Rietveld [10] in 1978 established a linear relationship between Ångström-Prescott coefficients and the mean relative sunshine duration. Stigter and Waryoba [11] in 1981 tested Rietveld's formula in East Africa and found good results. In the same way, researchers like Da Mota et al. [12] in 1977, Flocas [13] in 1980, Malek [14] in 1979 had already used these relations or tested the relations proposed by Rietveld respectively in Brazil, Greece and Iran and obtained interesting results. Obviously the linear correlation coefficient of this relation is better when the stations used are not too dispersed. Gariepy [15] in 1980 proposed an empirical relationship linking mean air temperature and precipitation. In 1984, Kilic and Ozturk [16] showed that Angstrom-Prescott coefficients are closely related to altitude, latitude and declination. Zabara [17] for his part found, a polynomial function of order three of the relative sunshine duration in 1986. Gopanathan [18] in 1988 proposed a relation linking the latitude, the altitude and the average relative sunshine duration. Zhou et al., in 2005 [19] studied the dependence of Angstrom-Prescott coefficients on latitude and altitude in China. In 2009, Liu et al. [20] proposed two relations in their study: one giving the coefficient a as a quadratic function of the mean temperature as well as the sum of the two coefficients; the other relates the two coefficients to altitude. According to the authors, the second relation gives good results for altitudes located around 2125 m.

The choice of a model is based on the availability of data related to the parameters that compose it. In Côte d'Ivoire, sunshine duration and solar radiation data are only available from a few agro-meteorological stations. To extend the estimation of Ångström-Prescott coefficients to any site in the country, it comes down to find a simple relationship linking them to the parameters of each site. To do so, we opted for the idea of Zhou et al., [19]. In fact, in a first study, we have already determined the Ångström-Prescott coefficients in nine (9) meteorological stations which will serve as a basis to construct a general formulation of them for each site in Côte d'Ivoire.

2. Methods and Material

2.1. Theoretical Aspect

The Ångström-Prescott equation establishes a linear relationship between the sky clearness index and the relative sunshine duration for a site and for a given period. To determine the Ångström-Prescott coefficients involved in this equation, it is necessary to have sunshine durations and solar radiation data corresponding to this period. However, in Côte d'Ivoire, as in certain regions of the world, these measures are not all time available. To overcome this lack of data, correlations are established between the Ångström-Prescott coefficients and the relevant parameters that influence them depending on the site. Table 1 below gives the general equations of the Ångström-Prescott coefficients obtained by a review of the literature. Liu et al. [2] have in their work studied the performance of these models in China. Readers are invited to refer to their study for more details. For our work and depending on the available data, we opted for the model of Zhou et al. [19] which links each Ångström-Prescott coefficient to the latitude and the altitude of station as follows:

$$\begin{cases} a = a_1 + b_1 cos\varphi + c_1 Z \\ b = a_2 + b_2 cos\varphi + c_2 Z \end{cases} \quad (1)$$

a_1, a_2, b_1, b_2, c_1, c_2 are constant coefficients to be calibrated, φ denotes the latitude and Z the altitude.

Table 1. A review of general equations of the Ångström-Prescott coefficients

N°	Equations	Author
1	$a = 0.29cos\varphi$ $b = 0.52$	Glover and McCulloch (1958)
2	$a = -0.27 + 1.75\frac{\bar{n}}{\bar{N}} - 1.34\left(\frac{\bar{n}}{\bar{N}}\right)^2$ $b = 1.32 - 2.93\frac{\bar{n}}{\bar{N}} + 2.3\left(\frac{\bar{n}}{\bar{N}}\right)^2$	Frère et al. (1975)
3	$a = 0.1 + 0.24\frac{\bar{n}}{\bar{N}}$ $b = 0.38 + 0.08\frac{\bar{n}}{\bar{N}}$	Rietveld (1978)
4	$a = 0.3791 - 0.0041T - 0.0176P$ $b = 0.4840 + 0.0043T + 0.0097P$	Gariepy (1980)
5	$a = 0.103 + 0.000017Z + 0.198cos(\varphi - \delta)$ $b = 0.533 - 0.165cos(\varphi - \delta)$	Kilic et Ozturk (1984)
6	$a = 0.395 - 1.247\frac{S}{S_0} + 2.680\left(\frac{S}{S_0}\right)^2 - 1.674\left(\frac{S}{S_0}\right)^3$ $b = 0.395 + 1.384\frac{S}{S_0} - 3.249\left(\frac{S}{S_0}\right)^2 + 2.055\left(\frac{S}{S_0}\right)^3$	Zabara (1986)
7	$a = 0.265 + 0.07Z - 0.135\frac{\bar{n}}{\bar{N}}$ $b = 0.401 - 0.Z108Z + 0.325\frac{\bar{n}}{\bar{N}}$ $a = -0.309 + 0.539cos\varphi - 0.0695Z + 0.290\frac{\bar{n}}{\bar{N}}$ $b = 1.527 - 1.027cos\varphi + 0.0926Z - 0.359\frac{\bar{n}}{\bar{N}}$	Gopinathan (1988)
8	$a = 1.8790 - 1.7516cos\varphi - 0.0205Z$ $b = 1.0819 - 0.5409cos\varphi + 0.0169Z$	Zhou et al. (2005)
9	$b = 4.33.10^{-4}T^2 - 0.0126T + 0.6289$ $a + b = -0.00966T + 0.8424$ $a = 0.0157Z + 0.1705$ $a + b = 0.0358Z + 0.7121$	Liu et al. (2009)

2.2. Solar Radiation Data

To carry out the study, we used data from nine (9) radiometric stations in Côte d'Ivoire covering 2006 to 2010. These data including the sunshine duration and the monthly average daily global solar radiation on horizontal surface collected by Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM) in charge of measuring meteorological parameters in Côte d'Ivoire are used at this purpose. Figure 1 shows the geographic positions of the selected meteorological stations.

Figure 1. Geographical positions of selected weather stations (SODEXAM)

Côte d'Ivoire is a West Africa country located between latitudes 4°N and 10°N. It is situated in two main climatic zones: the humid tropical climate in the south and the Sudanese climate in the north. Overall, Côte d'Ivoire has a relatively flat and slightly uneven relief, made up of plains in the North and plateaus in the South. Only the region of Tonkpi (Man) has mountainous relief. The mountain peaks do not exceed 1,300 meters in altitude, with the exception of Mount Nimba, located on the border with Guinea which culminates at 1,752 meters.

Table 2 shows the geographic coordinates of the sites as well as the measurement periods.

Table 2. Geographical coordinates of the sites and periods of the measurements

Station	Latitude (°)	Longitude (°)	Elevation (m)	Period
Abidjan	5.260291	-3.927276	8	2006-2010
Adiaké	5.286841	-3.302014	39	2006-2010
Bondoukou	8.016067	-2.762753	370	2006-2010
Daloa	6.87669	-6.45161	277	2006-2010
Dimbokro	6.649426	-4.704057	92	2006-2010
Gagnoa	6.132974	-5.95177	210	2006-2010
San-Pédro	4.746199	-6.660735	30	2006-2010
Sassandra	4.951934	-6.088562	66	2006-2010
Tabou	4.41397	-7.363371	21	2006-2010

The coefficients of the Ångström-Prescott equation, a and b were determined by linear regression using the least squares method relating the monthly mean daily clearness index to the relative sunshine duration at each station. The a and b values are obtained from data covering the period 2006 to 2010, collected annually in each weather station. The results obtained in a recent study are shown in Table 3.

Table 3. Linear regression results for each station

Station	a	b	$a+b$	R^2
Abidjan	0.2168	0.4179	0.6347	0.9838
Adiaké	0.2210	0.4066	0.6276	0.9801
Bondoukou	0.2652	0.3907	0.6559	0.9843
Daloa	0.2156	0.4182	0.6338	0.9828
Dimbokro	0.2707	0.3808	0.6515	0.9886
Gagnoa	0.2154	0.4173	0.6327	0.9776
San-Pédro	0.2176	0.4159	0.6335	0.9834
Sassandra	0.2169	0.4172	0.6341	0.9780
Tabou	0.2165	0.4144	0.6309	0.9916

From the calibration results obtained, we parameterized the Ångström-Prescott coefficients (1) in order to extend their determination to each site in the country even where no measurement is available. Multiple regressions are used to determine the parameters of the equations contained in (1) and the following results are obtained:

$$\begin{cases} a = -19.996cos\varphi - 0.00024297Z + 20.1474 \\ b = 12.877cos\varphi + 0.00017255Z - 12.4211 \end{cases} \quad (2)$$

In these equations, the altitude z is expressed in meters (m).

2.3. Analysis Methods

After determining the parameters of the Ångström-Prescott coefficients, the model is evaluated by comparing the calibrated and estimated values. The performance of the model is determined through the mean square error (RMSE), the mean bias error (MBE), the mean absolute bias error (MABE), the statistical t-test (t-stat) and the Nash-Sutcliffe coefficient (NSE) defined as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(c_i - m_i)^2} \quad (3)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(c_i - m_i) \quad (4)$$

$$MABE = \frac{1}{n}\sum_{i=1}^{n}|c_i - m_i| \quad (5)$$

$$t - stat = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \quad (6)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(m_i - c_i)^2}{\sum_{i=1}^{n}(m_i - m_a)^2} \quad (7)$$

where, n is the number of data used, c_i the estimated values , m_i the calibrated values and m_a is the mean of calibrated values.

RMSE and MBE are the most common indicators used to compare models in the field of solar radiation estimation. The RMSE provides information on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the estimated and calibrated values. The MBE on the other hand, shows the overestimation or the underestimation of the calculated values. Low values of RMSE and MBE are desired but depending on the data, some fluctuations may be observed. Togrul [21] showed that the isolated use of RMSE and MBE is not an adequate method for evaluating the performance of the model and concluded that the addition of the statistical t-test gave reliable and explanatory results for the evaluation and comparison of solar radiation models [22]. Jacovides [23,24] also demonstrated that the separate use of the RMSE and MBE indicators can lead to poor selection of the best model. He generally recommended using the statistical t-test in conjunction with RMSE and MBE to reliably assess model performance. The MABE measures the average of the absolute differences between predicted and calibrated values. Low values of MABE are also desired. The statistical t-test is determined from the mean squared error and the mean bias error. In this article, as suggested, we use the statistical t-test in conjunction with the RMSE and the MBE, for the evaluation of the model, assuming that the smaller the value of the statistical t-test, the better the performance of the model. To determine if a model is statistically significant, the absolute value of the calculated statistical t-test must be less than the critical value of the t-test, obtained from the tables. Referring to the number of data used (n = 9) and at a 95% significance level, the critical value of the statistical t-test is 1.860 for a one-sided test. In regression procedures, NSE is equivalent to the coefficient of determination (R^2). Values of the NSE nearer to 1, suggest a model with more predictive skill.

3. Results and Discussion

The results of the Ångström-Prescott coefficients predicted in the nine (9) meteorological stations are presented in Table 4. The various indicators and statistical tests are also given in Table 5. According to Table 4, the values of the estimated coefficient a range from 0.2056 to 0.2636 with coefficient of variability of 2.9 % while those of b range from 0.3851 to 0.4184 with coefficient of variability of 8.5 %. Obviously, the predicted Ångström-Prescott coefficients cover practically the same intervals as those calibrated. By observing Table 5, the values of NSE close to 1 (0.7653197 and 0.99734601) of the two coefficients, indicate that the estimated values are close to the calibrated ones. This remark is also confirmed by the comparative bar graphs of the estimated and calibrated coefficients in Figure 2 and Figure 3 and the RMSE in Table 5 indicates that the absolute mean deviation between the estimated and calibrated values is 0.0063 for b and 0.0094 for a. Those values are satisfactory for they have no large magnitude. The MBE in Table 5 shows that the model slightly underestimates the values of the Ångström-Prescott coefficients.

Table 4. Values of Ångström-Prescott coefficients

Cities	b_{exp}	a_{exp}	b_{theo}	a_{theo}
Abidjan	0.4179	0.2168	0.4030	0.2337
Adiaké	0.4066	0.221	0.4078	0.2279
Bondoukou	0.3907	0.2652	0.3939	0.2569
Daloa	0.4182	0.2156	0.4110	0.2279
Dimbokro	0.3803	0.2707	0.3851	0.2636
Gagnoa	0.4173	0.2154	0.4184	0.2148
San-Pédro	0.4159	0.2179	0.4169	0.2127
Sassandra	0.4172	0.2169	0.4192	0.2100
Tabou	0.4144	0.2165	0.4213	0.2056

Notes: a_{exp} and b_{exp} are AP calibrated coefficients and a_{theo} and b_{theo} are the estimated ones.

Table 5. Values of the various indicators and statistical tests of the coefficients *a* and *b*

	b	a
MBE	-0.00017254	-0.00042828
MABE	0.00471422	0.00825164
RMSE	0.00633772	0.00935143
NSE	0.7653197	0.99734601
t-stat	0.07205623	0.12129825

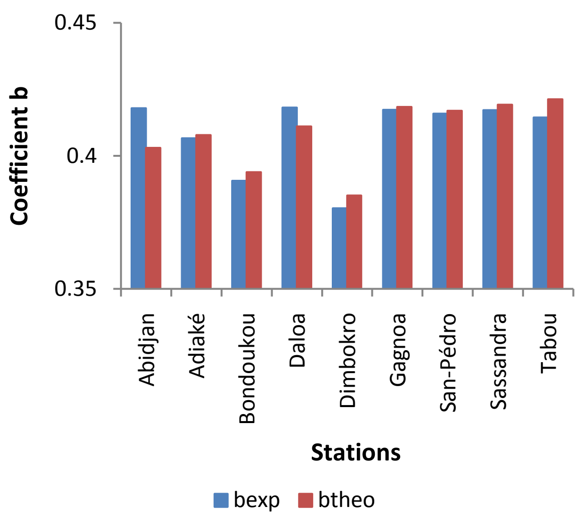

Figure 2. Comparative bar graphs of the estimated and calibrated coefficients b

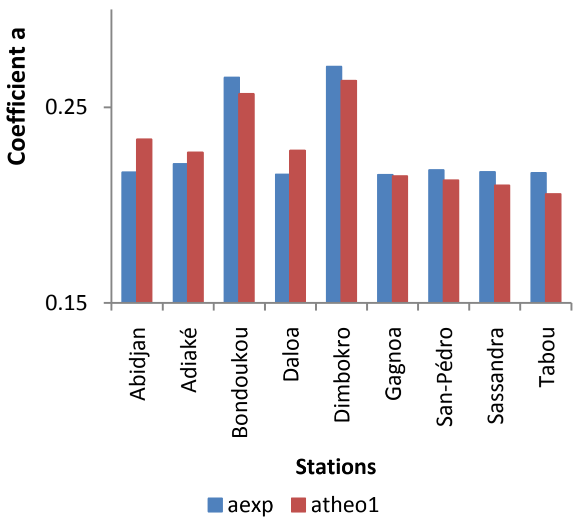

Figure 3. Comparative bar graphs of estimated and calibrated ***a*** coefficients

Meanwhile Figure 2 and Figure 3 show that the model predicts coefficient b better than coefficient a. In fact, the statistical indicators of coefficient b are in absolute value much lower than those of coefficient a. This confirms that the estimate of the coefficient b is better than that of the coefficient a.

The Ångström-Prescott coefficients should be used to estimate the monthly mean daily global irradiation in different sites of Côte d'Ivoire. The accuracy of their values leads to the accuracy of the estimated solar radiation. As underlined by Liu et al. [2] the accurate prediction of coefficient a is more important than that of coefficient b in estimating global solar radiation. Therefore, priority should be given to parameter models having higher accuracy for coefficient a. To improve the accuracy of the coefficient a we have correlated it to the coefficient b by a polynomial function of degree two as shown in Figure 4.

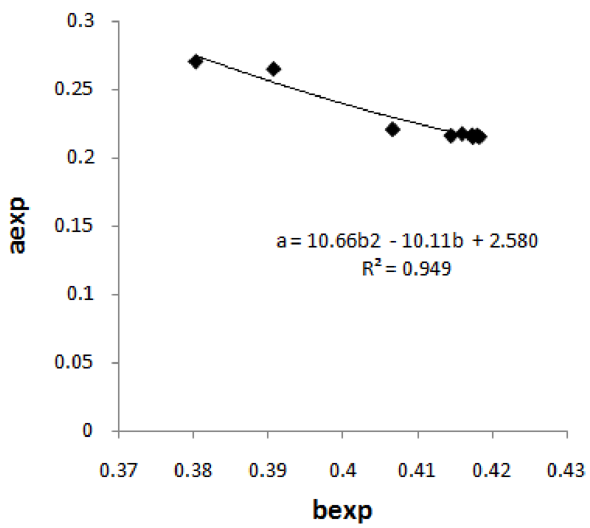

Figure 4. Change in coefficient ***a*** as a function of coefficient *b*

The relation obtained is:

$$a = 10.66b^2 - 10.11b + 2.580 \quad (8)$$

With this new equation, the statistical indicators calculated are shown in Table 6 and the comparative bar graphs of the change in coefficient a is given in Figure 5.

Table 6. Values of the various indicators and statistical tests of coefficient *a*

	a_{theo1}	a_{theo2}
MBE	-0.00042828	0.00084908
MABE	0.00825164	0.00346367
RMSE	0.00935143	0.00498464
NSE	0.99734601	0.99924593
t-stat	0.12129825	0.45735957

Notes: 1 indicates the first results of coefficient a and 2 denotes the second ones.

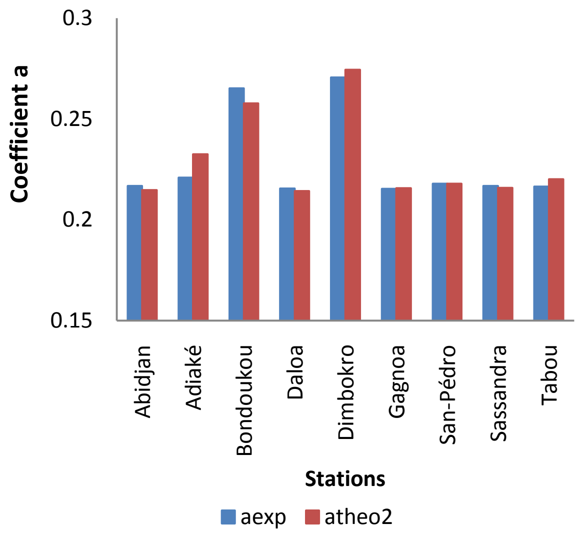

Figure 5. Comparative bar graphs of the estimated and calibrated *a* coefficients

Figure 5 shows a clear improvement in the estimate of the coefficient a by relation (8) compared to figure 3. The statistical indicators in Table 6 show a significant drop in MABE and RMSE of 58.02 % and 46.70 % respectively. Thus, the estimated values of the coefficient a are close to those calibrated. The positive value of the MBE indicates that the model overestimates the values of the coefficient a, but this overestimation is slight in magnitude.

Ultimately, this second method improves the accuracy of coefficient a. This analysis allows us to retain the following two equations:

$$\begin{cases} b = 12.877 cos\varphi + 0.00017255z - 12.4211 \\ a = 10.66b^2 - 10.11b + 2.580 \end{cases} \quad (9)$$

In that use, a two-step procedure is needed: predicting coefficient b first and then coefficient a in the second step by substituting the value of b in the expression of a. These equations validly estimate the Angström-Prescott coefficients over the entire extent of Côte d'Ivoire by knowing for each site its latitude and altitude.

4. Conclusion

Attempts have been made in this work to propose parametrized annual Angström-Prescott coefficients in

Côte d'Ivoire using data from nine (9) weather stations, sampled in monthly mean daily global radiation and sunshine duration. The Angström-Prescott coefficients are correlated to latitude and altitude. The performance of the models was evaluated using some errors indicators. The study found that the accuracy of coefficient a is less that this of coefficient b. To improve the accuracy of coefficient a, a polynomial approach is suggested linking it to coefficient b. The global results obtained show a strong correlation with a high determination coefficient for each parameter confirmed by values of NSE close to 1. These results indicate that the two equations proposed in the model can be used satisfactorily for the estimation of Angström-Prescott coefficients in any site in Côte d'Ivoire.

Nomenclature

a	Ångström-Prescott regression coefficient
b	Ångström-Prescott regression coefficient
$\bar{n}$	Mean sunshine duration (h)
$\bar{N}$	Mean maximum sunshine duration (h)
T	Temperature (℃)
P	Precipitation (mm)
Z	Altitude (m)
φ	Latitude (°)
δ	Declination (°)
S	Sunshine duration (h)
S_0	Day length (h)

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