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GLOBAL SOLAR RADIATION RECORDS AND MODELLING WITH BIRD AND BRISTOW-CAMPBELL MODELS AT LA PAMPILLA STATION IN AREQUIPA, PERU

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ABSTRACT

This article contains daily records of global solar radiation from 2009 to 2013 from the station of the National University of San Agustin of Arequipa (UNSA), complemented with the Bristow-Campbell model and Bird model to fill data gaps. The Bristow-Campbell model was implemented with maximum and minimum temperatures data at La Pampilla Station from National Service of Meteorology and Hydrology of Peru (SENAMHI) and at UNSA station. The Bird model was implemented considering physics characteristics of the area. Both models were calibrated using RMSE, R2, d and PBIAS statistics, where it was found that Bristow-Campbell model performance is better than Bird Model. From the sensitivity analysis with Monte Carlo analysis, for the parameters of the Bristow-Campbell model, the parameter cB is the most influential in solar radiation calculation and the Bird model is more sensitive to the surface albedo.

KEYWORDS: Global Solar Radiation, Bristow-Campbell, Bird, Montecarlo Analysis, Calibration.

1. RATIONALE

Solar radiation is the primary energy source for the development of biophysical and ecological processes, and has an important role in multiple applications on topics related to energy and climate change [1] as well as in other fields of science and engineering. In many regions of Peru the development of agriculture has a high influence on the country's economy, so accurate knowledge of solar radiation is important for irrigation programming and the design and installation of sustainable photovoltaic systems [2]. In hydrology and water quality analysis, radiation is a crucial data, effort obtaining it near to the study area was perform by [3]. In addition, different studies of environmental importance as [4–6]could be achieved with the confidence radiation data. However, unlike other measurable and easily accessible meteorological parameters, solar radiation has a measurement involving high costs for precision instrumentation and its maintenance, so in many countries it is limited, especially in Peru [7]. Therefore, it is common practice to estimate daily averages of global radiation using conventional and computational methods, based on the limited local information available.

Thus, in the present study, the Bristow-Campbell and Bird models was applied to get the best estimation of the daily average of global solar radiation at La Pampilla station in Arequipa, since both models require data that can be easily obtained. The Bristow-Campbell model [8] presents better predicative capacity for the estimation of daily solar radiation when only daily maximum and minimum temperatures are available [9]. The Bird model [10], allows to obtain data of global solar radiation in any location and at every hour of the year, adjusting characteristic data of the area such as the time zone, atmospheric pressure, water vapor thickness of atmosphere, aerosol optical depth at 380 nm and 500 nm, forward scattering of incoming radiation and surface albedo.

2. PROCEDURE

2.1. *Study*

The study area is located in the National University of San Agustin of Arequipa, Peru, at the following coordinates 16°24'13.72" South Latitude and 71°31'28.37" West Longitude and at an altitude of 2372 meters above sea level (Fig. 1)
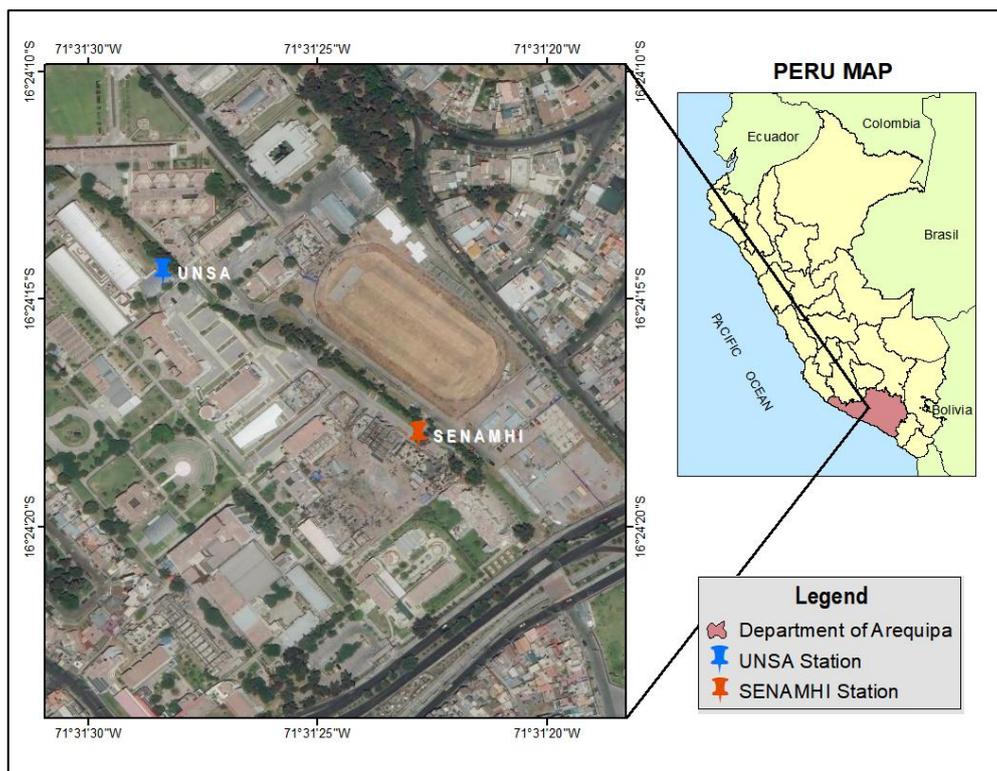

Fig 1. Location of the SENAMHI and UNSA stations.

2.2. *Sample collection and analysis*

For this study, daily data of global solar radiation were obtained from the Vantage Pro2 Plus weather station of the National University of San Agustin of Arequipa (UNSA) from 2009 to 2013. This station is formed by a set of integrated sensors (Integrated Sensor Suite – ISS). The wireless ISS is powered by solar power and transmits data to the console via a

low-power transmitter. The ISS Plus has a solar radiation sensor and an ultraviolet radiation sensor, its technical characteristics are shown in Table 1.

Table 1: Technical characteristics of the Vantage Pro2 Plus station.

Operating temperature	-40 ^oC to $+65$ ^oC
Spectral response (10% points)	$400 - 1100$ nm
Dimensions (Length · Width · High)	$51 \cdot 70 \cdot 57$ mm
Weight	226 g
Resolution and units	1 W/m^2
Distance	$0 - 1800$ W/m^2
Solar power panel	0.5 Watts/0.75 Watts

In addition, two sets of minimum and maximum temperature meteorological data were obtained for the year 2009-2013, one of them obtained from the station La Pampilla belonging to the network of stations of the National Service of Meteorology and Hydrology of Peru (SENAMHI) during the years 2001 to 2015 and the other own of the UNSA. These data were organized on a daily basis and those dates in which there were missing daily data were eliminated. The data recorded as well as the simulated data are presented in Supplementary Table S1.

2.3. Application of global solar radiation models

2.3.1. Bristow-Campbell model

The Bristow-Campbell model [11] is a physical model that allows to estimate the daily or monthly global solar radiation as a function of the extraterrestrial solar radiation and the difference between the maximum and minimum temperatures in a given area. To determine the daily global solar radiation with this model, the following equations were applied:

$$\frac{H_g}{H_{eh}} = a_B[1 - exp(-b_B \Delta T^{C_s})]$$

$$H_{eh} = \frac{24}{\pi} \cdot I_{sc} \cdot E_o$$
$$\cdot \left[sin\, \delta \right.$$
$$\cdot sin\, \theta \cdot \omega_h \cdot \frac{\pi}{180}$$
$$\left. + cos\, \delta \cdot cos\, \theta \cdot sin\, \omega_h \right]$$

$$E_0 = 1 + 0{,}033 \cdot cos\left(\frac{2 \times \pi \times d_n}{365}\right)$$

$$\delta = sin^{-1}\left[0{,}4 \times sin\left(\frac{360 \times (d_n - 82)}{365}\right)\right]$$

$$\omega_h = \pm cos^{-1}(-tan\, \emptyset \cdot tan\, \delta)$$

Where H_g is the global solar radiation (Wh/m^2), H_{eh} is the extraterrestrial solar radiation (Wh/m^2), ΔT is the maximum and minimum temperature difference (°C), E_o is the correction factor of the eccentricity of the Earth orbit, d_n is the Julian day, δ

is the solar declination in degrees, ω_h is the hourly angle measured in degrees for a horizontal surface, I_{sc} is the solar constant (W/m^2) and of the coefficients (a_B, b_B, c_B) of the Bristow-Campbell model, a_B represents the maximum characteristic value of each study area that depends on air pollution and altitude, b_B and c_B determine the effect of the temperature increase on the maximum transmissivity of the atmosphere.

For this study, the global solar radiation was calculated with the Bristow-Campbell model from the database of maximum and minimum temperatures of the year 2013 of the La Pampilla station of the SENAMHI and the station of the Professional School of Physics of the National University of San Agustin of Arequipa; for both stations, the coefficients a_B, b_B, c_B with which they worked were 0.76, 016 and 0.91 respectively, which correspond to the coefficients of the Station La Pampilla, according to Table 2.

Table 2: Values of coefficients of the Bristow-Campbell Model per station.

Meteorologic station	a_B	b_B	C_B
Costa			
Miraflores	0,75	0,04	1,49
A. Von Humboldt	0,68	0,06	1,42
San Camilo	0,79	0,09	1,05
Sierra			
Bambamarca	0,66	0,23	0,80
Weberbauer	0,75	0,04	1,28
Cosmos	0,70	0,03	1,62
Huayao	0,78	0,11	0,97
Granja Kcayra	0,74	0,11	0,92
Chuquibambilla	0,78	0,19	0,76
Puno	0,82	0,20	0,87
Characato – La Pampilla	0,76	0,16	0,91
Selva			
San Ramón SM	0,68	0,02	1,86
El Porvenir	0,60	0,06	1,21
Bellavista	0,70	0,06	1,22

source: Baigorria et al., 2004

2.3.2. Bird Model

Bird's model [10] is a simplified model of clear sky of direct and diffuse radiation on horizontal surfaces, it is composed of simple algebraic relations, which requires available meteorological information making it easy to apply, this model has been built from the formulations and constructions of 5 other radiation models, generating a robust model of easy application. However, it was not calibrated with observed data due to the difficulty involved in having long records of this variable.

The model has been implemented in VBA code by Washington State Department of Ecology (available at https://ecology.wa.gov/Research-Data/Data-resources/Models-

spreadsheets/),whose basic equations are:

$$I_d = 0.9662\, I_o(cos\, Z)\, T_R T_o T_{UM} T_W T_A$$
$$I_{as} = 0.79\, I_o T_o T_{UM} T_W T_{AA}$$
$$I_T = (I_d + I_{as})/(1 - r_g r_s)$$

Where, I_d is Direct solar irradiance on a horizontal surface (W/m²), I_{as} is Solar irradiance on a horizontal surface from scattered light, I_T is Total (global) solar irradiance on a horizontal surface (W/ m²), I_o is Extraterrestrial solar irradiance (1353 W/ m²), Z is Angle between a line to the sun and the local zenith (zenith angle in degrees), T_R is Transmittance of Rayleigh scattering, T_o is Transmittance of ozone absorptance, T_{UM} is Transmittance of absorptance of uniformly mixed gases (carbon dioxide and oxygen), T_W is Transmittance of water vapor absorptance, T_A is Transmittance of aerosol absorptance and scattering, T_{AA} is Transmittance of aerosol absorptance, r_g is Ground albedo and r_s is Sky, or atmospheric albedo.

2.4. Calibration and sensitivity analysis

Both models were calibrated using mean square error (RMSE), and indicators such as coefficient of determination (R²), concordance index (d), and PBIAS bias have been estimated as a means of evaluating the results. In addition, a sensitivity analysis was performed to determine the correlation between the radiation data and the adjustment parameters through spearman's nonparametric Rho test, as well as the contribution to the variance of the target variable. For this purpose, a uniformly distributed Monte Carlo analysis is performed using YASAI tool [12]. For this stage, data from 2013 were used because the daily global solar radiation records obtained from the UNSA station were more complete for this year.

3. DATA, VALUE AND VALIDATION

3.1. Analysis of estimated global solar radiation

For the Bristow-Campbell model, the estimated results, based on the maximum and minimum temperature data from the UNSA and SENAMHI stations, showed that the PBIAS bias and the concordance index d are within the optimal interval, the coefficient of determination R² does not reach the optimal value, but is greater than the Bird model, and finally the RMSE for both presents a smaller variation.

For Bird's model, the determination of the calibration statistics (Table 3) shows values close to the optimal ones with respect to the PBIAS bias, and the concordance index d, on the other hand shows a low coefficient of determination R² and a high RMSE, which indicates that the results are of regular confidence, this can be verified in Fig5.

Table 3: Calibration statistics of applied global solar radiation models.

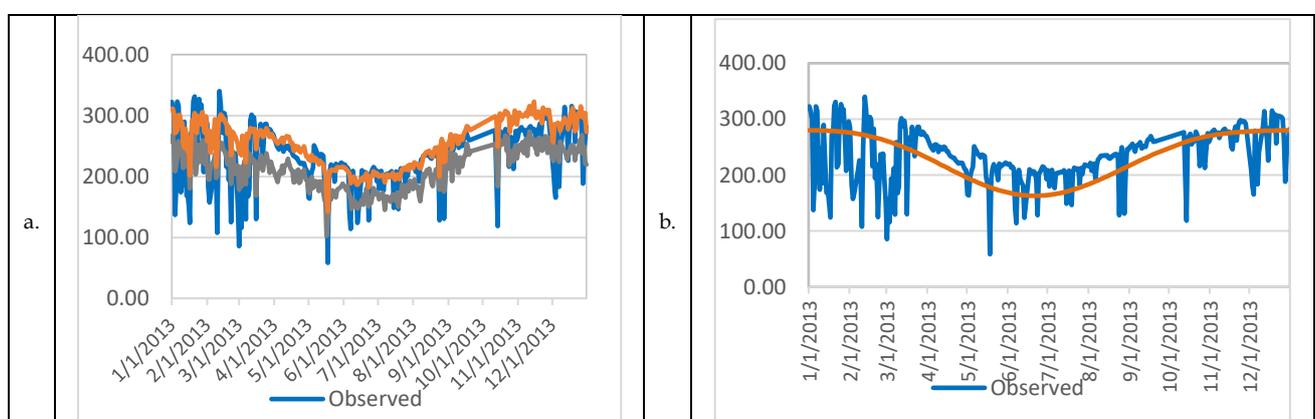| Statistic	Expression	Optimal value	Bird Model	Bristow-Campbell Model	
				UNSA	SENAMHI
RMSE	$\sqrt{\dfrac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}$	0	47.831	28.633	25.648
R2	$[\dfrac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}]^2$	1	0.195	0.474	0.460
d	$1 - \dfrac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(\|P_i - \bar{O}\| + \|O_i - \bar{O}\|)^2}$	1	0.677	0.735	0.768
PBIAS	$\dfrac{\sum_{i=1}^{n}O_i - P_i}{\sum_{i=1}^{n}O_i}\, x\, 100$	0	1.585	9.498	-9.051

Fig2. a. Comparison of estimated global solar radiation with the Bristow Campbell model (Radiation in W/m2) b. Comparison of estimated global solar radiation with the Bird model model (Radiation in W/m2).
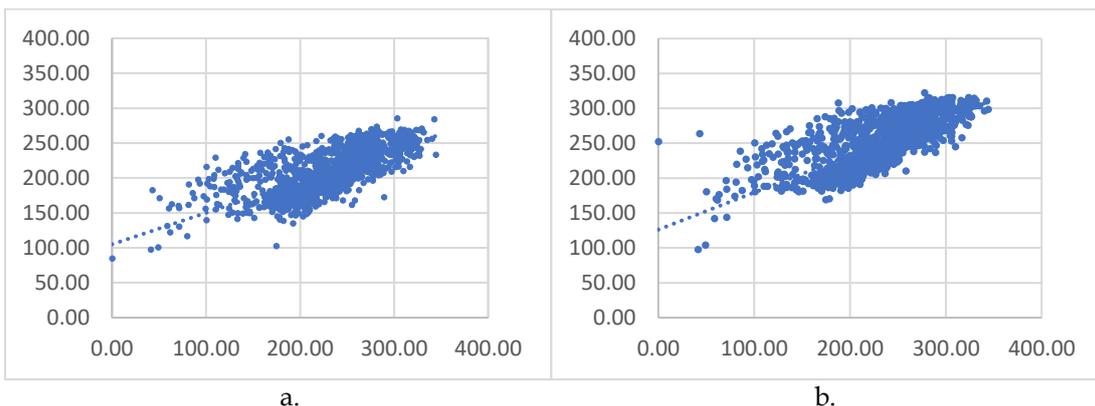
a.   b.

Fig3 a. Scatter plot of observed data and estimated data at the UNSA station with the Bristow-Campbell model (2009-2013) b. Scatter plot of observed data and estimated data at the SENAMHI station with the Bristow-Campbell model (2009-2013).
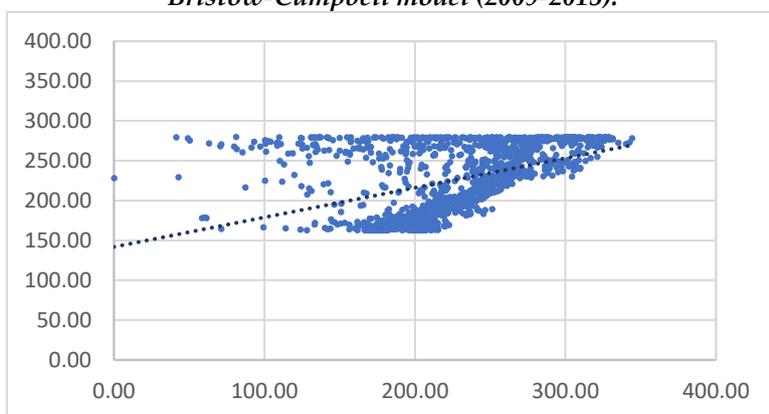

Fig4. Scatter plot of the actual data and the estimated data at the SENAMHI station with the Bird model (2009-2013).

3.2. Sensitivity analysis

The sensitivity analysis with the Monte Carlo analysis for the Bristow-Campbell model, showed that the coefficient c_B has a greater influence on the estimation of the daily global solar radiation, then follows the coefficient b_B and finally the coefficient a_B with a lesser influence on the calculations.

Table 4: Sensitivity of the parameters (aB, bB, cB) of the Bristow-Campbell model.

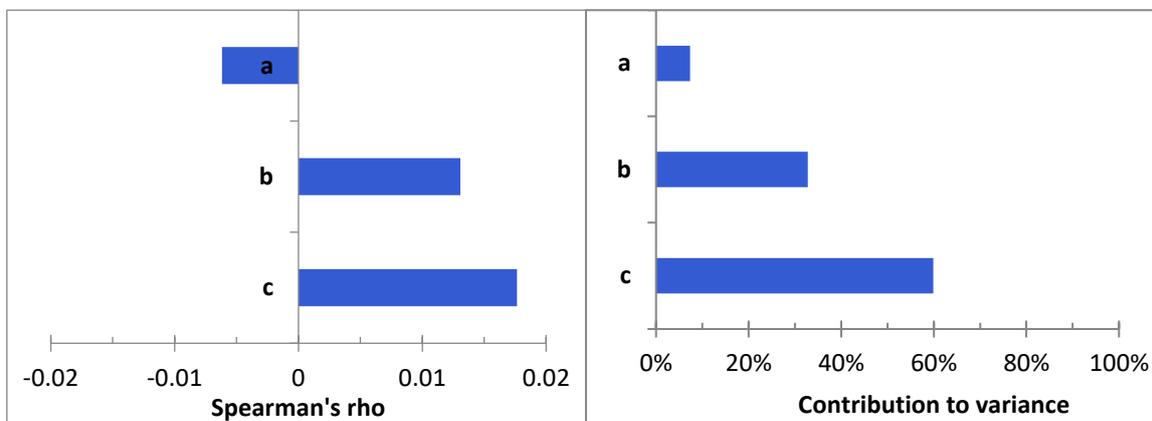| Parameter	Spearman's Rho	Contribution to variance
a_B	-0.0062	7.36%
b_B	0.0131	32.79%
c_B	0.0176	59.85%

Fig5. Sensitivity indicators of the Bristow-Campbell model.

Regarding the sensitivity analysis of the Bird model, it was found that the Surface Albedo is the parameter with the greatest effect in the calculations of the radiation, the other parameters have a uniform and minor effect in the calculation of the radiation, however, the cloud overture is the parameter that proves to have a lower impact on the calculations made.

Table 5: Sensitivity of Bird model parameters.

Parameter	Spearman's Rho	Contribution to variance
Surface albedo	0.7860	72.04%
Aerosol optical depth at 500 nm	-0.2865	9.57%
Water vapor thickness of atmosphere	-0.2419	6.82%
Forward scattering of incoming radiation	0.2226	5.78%
Aerosol optical depth at 380 nm	-0.2215	5.72%
Cloud cover fraction	-0.0241	0.07%
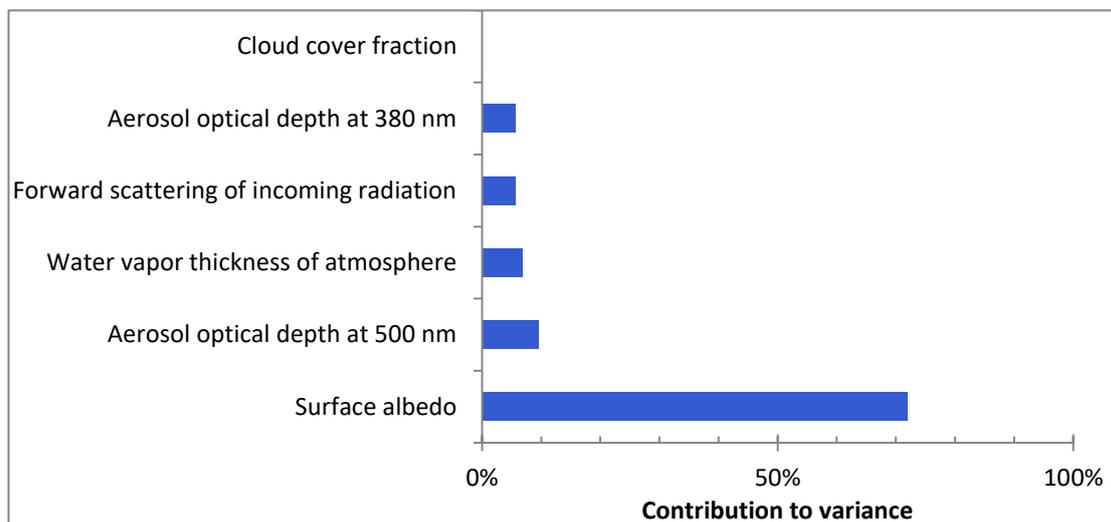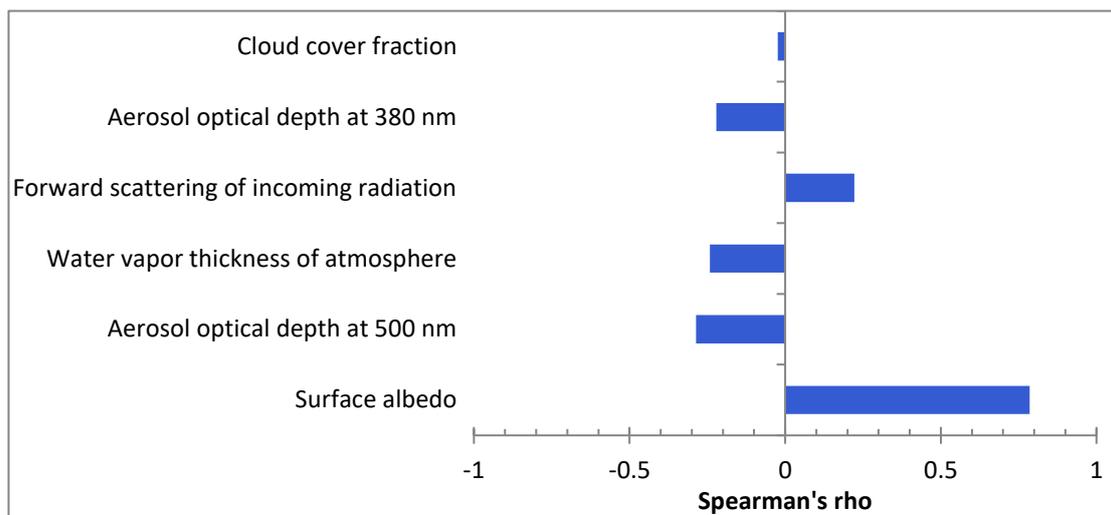
Fig 6. Sensitivity indicators of the Bristow-Campbell model.

Specifications Table

Subject area	*Physic*
Compounds	*Global solar net radiation*
Data category	*Sensor measurement and computational simulation*
Data acquisition format	*Direct measurement and estimated*
Data type	*Raw, analyzed, simulated*
Procedure	*Direct measurement through automatic station, data statistic processing and modeling to complete data series*
Data accessibility	*Data is available in this article.*

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