Supplementary Materials

1. Basic Theory and Parameters

In this section, we present the basic theory, as well as parameters, of the attenuation of DNI due to the presence of aerosols in the atmosphere. DNI is given at any height as a function of the DNI_{TOA} at the Top of Atmosphere [24]:

$$DNI = DNI_{TOA} \times \exp\left(-\tau/\cos(Z)\right) \tag{1}$$

where τ is the optical depth of the atmospheric column and Z is the solar zenith angle. The aerosol forcing F is defined as:

$$F = DNI_a/DNI_b = \exp\left(-(\tau_a - \tau_b)/\cos(Z)\right) \tag{2}$$

DNI_a is the DNI measured in an aerosols-present atmosphere, whereas DNI_b is the calculated DNI with the assumption of a clean-dry atmosphere. The difference in optical depths between the aerosols-present atmosphere and the no-aerosols (clear-dry) atmosphere is:

$$\Delta\tau = \tau_a - \tau_b \tag{3}$$

Similarly to Eq. (2), we can consider F as a relationship between the DNI at a reference surface level DNI_{sfc}, and the $DNI_{\Delta z}$ measured at a height Δz above that level. The expression of F is then:

$$F = DNI_{sfc}/DNI_{\Delta z} = \exp\left(-\tau_{\Delta z}/\cos(Z)\right) \tag{4}$$

Thus, we obtain the optical depth of the atmosphere layer, between the surface (reference level) and any height Δz, as follows:

$$\tau_{\Delta z} = -\ln\left(DNI_{sfc}/DNI_{\Delta z}\right) \times \cos(Z) \tag{5}$$

From this formulation given by Sengupta and Wagner [24], it is possible to calculate the optical depth from measurements of the DNI at different heights. It is a useful, yet simple, formulation to calculate the Aerosols Optical Depth (AOD), which characterizes the atmospheric haziness caused by aerosols [182].

2. Aerosols Optical Depth (AOD) τ

The aerosols present in the atmosphere vary largely in number, size, composition and form. Ångström turbidity coefficient and exponent characterize the DNI attenuation due to the optical effect of aerosols on solar radiation [19]. According to Ångström [182], the AOD's expression is:

$$AOD = \tau = \beta\lambda^{-\alpha} \tag{6}$$

where λ is the wavelength, β and α are Ångström coefficient and exponent resp. Ångström coefficient β reflects the quantity of aerosols present in the vertical direction of the atmosphere, for $\beta > 0.2$ the atmosphere is considered as hazy. Ångström exponent α is inversely proportional to the size of aerosols, if $\alpha > 2.5$ then there are more small-size particles than large ones. For most natural atmospheres, the value of β vary from 0.0 to 0.5 and $\alpha = 1.3 \pm 0.2$ [19].

3. Linke's Turbidity Factor T_L

In 1922, Linke [183] proposed to express the total optical thickness as the product of two terms, the optical thickness of the clear-dry atmosphere (water-free and aerosols-free) δ_{cda}, and the Linke Turbidity Factor T_L which represents the number of clear dry atmospheres that produce the same attenuation as a hazy atmosphere [110, 183]. The expression proposed by Linke is:

$$DNI = I_0\, exp(-\delta_{cda} \times T_L \times AM) \quad (7)$$

I_0 is the normal incident extraterrestrial irradiance, and AM is the air mass. Both δ_{cda} and T_L are functions of the air mass AM, this is a consequence of the strong dependence of Rayleigh scattering upon the wavelength [110, 125].

4. Air Mass

It characterizes the ratio of the mass of the atmosphere that the radiation beam passes through, to the mass that the normal beam (sun at zenith) passes through. At sea level with sun at zenith: AM = 1. The relative air mass is obtained by Kasten's formula [184]:

$$AM_r = 1/(cos(Z) + 0.15(93.885 - Z)^{-1.253}) \quad (8)$$

where Z is the solar zenith angle. The absolute air mass AM is then derived using the equation:

$$AM = AM_r \times P_1/P_0 \quad (9)$$

P_0 is the standard pressure (1013.25 mbar), and P_1 is the actual site pressure in mbar [87].

5. Astronomical Input Parameters of CSI Models

5.1. Solar Constant

The solar constant is defined as the yearly mean value of the direct normal irradiance DNI. The value adopted by the World Radiation Center (WRC) is I_{0c} = 1,367 W/m². However, due to the eccentricity of Earth's orbit, the distance Earth-Sun varies throughout the year, taking this into account, the corrected daily value of the solar constant is given as a function of the Julian day number N_j [83]:

$$I_0 = I_{0c}(1 + 0.033 \cos(360N_j/365)) \quad (10)$$

5.2. Declination Angle

The declination angle δ is the tilt between Earth's axis of rotation and the normal to its plane of revolution. $|\delta| \leq 23.45$ (positive value north). It can be calculated by the equation [83]:

$$\delta = 23.45 \sin((N_j + 284) \times 2\pi/365) \quad (11)$$

6. Scattering Theories: Rayleigh Theory & Mie Theory

Dependently on the particle diameter, the adequate theory that governs the scattering of aerosols is as follows [37]:

a) $\pi D/\lambda < 0.6/n$. where n is the refraction index, the governing theory is Rayleigh scattering theory for particles with diameters inferior to the wavelength of incident light.

b) $0.6/n < \pi D/\lambda < 0.6$. The scattering occurs according to Mie particle theory.

c) $\pi D/\lambda > 0.6$. If the diameter is big enough to satisfy this condition, the light is reflected.

References

183. Linke F. Transmission-Koeffizient und Trubungsfaktor. *Beitraege. Phys. fr. Atomos.* 1922;10:91-103.
184. Kasten F. A new table and approximation formula for the relative optical air mass. *Arch Meteor. Geophy. B* 1965;14:206-223.