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Reformulation of the Used Model to Estimate Soil Temperature

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Abstract: The Earth is permanently surrounded by cloud cover that, particularly, is an essential component in the planet's energy balance. In turn, cloud cover intervenes in the main conditioning factor for soil temperature: solar radiation. In particular, the soil thermal amplitude should be dampened with the attenuation of solar radiation. However, the scientific community rarely analyzes this relationship, neglecting the model that is used to estimate the soil temperature. In this context, the present study seeks to reformulate the model by inserting a variable referent to cloud cover. Thus, to achieve this objective, a physical-mathematical review of the heat flow in the vertical profile of soil is performed. The reformulated model indicates the influence of cloud cover, intervening for both the soil's heating (nighttime period) and cooling (daytime period). Finally, the reformulated model should be employed to estimate the soil thermal behavior (in particular, on "overcast sky" days).

Keywords: energy balance; cloud cover; soil temperature

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1. Introduction

Solar radiation is responsible for triggering a large part of the chemical, physical, and biological processes in the soil-plant-atmosphere system [1,2]. This is the primary energy source for the processes that occur on the planet, and, as it reaches the surface, triggers the heating of the entire vertical profile of the soil [3]. Therefore, it is the main conditioning factor for soil temperature [4,5]. Soil temperature is related to the processes of soil–plant interactions and, in particular, directly intervenes in the following processes: seed germination, growth rate, functional activity of the root system, and the development of diseases, among others [6,7]. In some situations, the growth of the aerial parts of plants (stems, branches, leaves, and flowers) has a relationship with the soil temperature being higher than the air temperature [8].

Soil temperature is considered one of the most important environmental elements for plant development [9]. This presents cyclical variations within a period of 24 h (daily cycle) and, in turn, are derived from the Earth's rotational movement. The simplest mathematical model is obtained assuming that: the soil temperature for the entire vertical profile oscillates as a pure harmonic function (sinusoidal) of time around an average value [10]. In this context, such cycles would be similar, differing "slightly" with respect to the magnitudes of temperatures. However, it is verified that an expressive variability is experimentally not predicted by the mathematical model.

On the other hand, cloud cover is a determinant for the planet's energy balance due to the high capacity for the attenuation of solar radiation [11]. Therefore, it comes to influence the aforementioned variability indirectly. However, this soil–atmosphere relationship is neglected by the model since there isn't a term referring to cloud cover [12]. According to [13], the model should only be applied to days without clouds (an idealized situation that differs from day-to-day). In this context, the present study seeks to reformulate the mathematical model by inserting a variable referring to cloud cover (particularly in the term referring to the soil thermal amplitude).

2. Material and Methods

2.1. Soil Heat Flux

Thermal equilibrium is made impossible by variations in the incidence of solar radiation at the surface, and the existence of a thermal gradient promotes the heat flux through the vertical profile of the soil [14,15]. The heat flux is associated with conduction and intraporous convection [16]. However, because water movement occurs slowly inside the soil, intraporous convection is neglected. In this context, conduction is the determining process for soil heat flux [11]. Figure 1 illustrates a volume element contained in a soil layer:

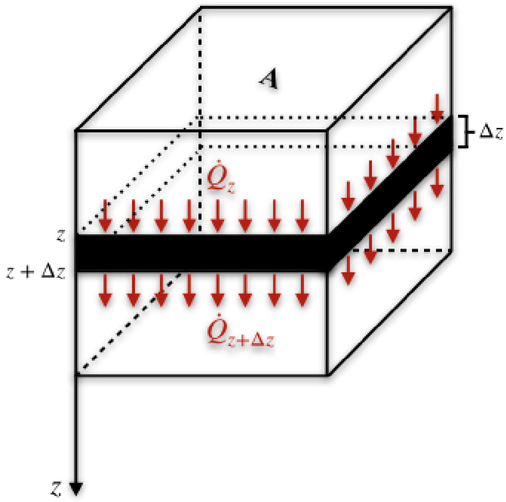

Figure 1. Volume element contained in a soil layer.

The soil layer has a density (ϱ), specific heat (c), and area normal to the direction of heat transfer (A). In the time interval (Δt), the energy balance for the volume element can be expressed as follows [17]:

(Heat conduction rate in z) − (Heat conduction rate in z + Δz) + (Heat generation rate in the volume element) = (Rate of variation of the energy contained in the volume element)

or

$$\dot{Q}_z - \dot{Q}_{(z+\Delta z)} + \dot{G}_{element} = \frac{\Delta E_{element}}{\Delta t} \quad (1)$$

Chemical reactions can release energy during the process and, thus, are characterized as secondary sources of heat in the soil. However, it is disregarded because it provides almost imperceptible soil changes. Equation (1) can be rewritten as follows:

$$\dot{Q}_z - \dot{Q}_{(z+\Delta z)} = \frac{\Delta E_{element}}{\Delta t} \quad (2)$$

The variation of the energy contained in the volume element:

$$\Delta E_{element} = E_{(t+\Delta t)} - E_t = Q \quad (3)$$

In Equation (3), $E_{(t+\Delta t)}$ and E_t refer to the energy contained in the volume element at the final and initial instants, respectively. In addition, the net amount of heat transferred during the entire process is represented by the variable (Q). This is obtained as follows:

$$Q = mc\Delta T = \varrho cV\left(T_{(t+\Delta t)} - T_t\right) = \varrho cA\Delta z\left(T_{(t+\Delta t)} - T_t\right) \tag{4}$$

In Equation (4), the variables refer to the properties of the volume element: m is the mass, ϱ is the density, c is the specific heat, V is the volume, A is the surface area, Δz is the thickness, and ΔT is the temperature variation. In addition, $T_{(t+\Delta t)}$ and T_t refer to the temperature at the final and initial instants, respectively.

Performing the substitutions in Equation (2):

$$\dot{Q}_z - \dot{Q}_{(z+\Delta z)} = \varrho cA\Delta z \frac{T_{(t+\Delta t)} - T_t}{\Delta t} \tag{5}$$

Dividing by $A\Delta z$:

$$-\frac{1}{A}\frac{\dot{Q}_{(z+\Delta z)} - \dot{Q}_z}{\Delta z} = \varrho c \frac{T_{(t+\Delta t)} - T_t}{\Delta t} \tag{6}$$

According to Fourier's law of heat conduction, and in the limit situation where $\Delta z \to 0$ and $\Delta t \to 0$ can be rewritten in differential form:

$$\frac{1}{A}\frac{\partial}{\partial z}\left(kA\frac{\partial T_{(z,\,t)}}{\partial z}\right) = \varrho c \frac{\partial T_{(z,\,t)}}{\partial t} \tag{7}$$

In Equation (7), k is the soil thermal conductivity. This is a function of the individual properties of those constituents that compose it [17]. The composition and air/water content vary in space and time, respectively [10]. In this context, the soil thermal conductivity is a variable property in space and time. In order to nullify the spatial variability, the soil is usually considered an isotropic medium (i.e., uniform properties in all directions). Therefore, the equation can be rewritten as follows:

$$\frac{\partial^2 T_{(z,t)}}{\partial z^2} = \left(\frac{\varrho c}{k}\right)\frac{\partial T_{(z,t)}}{\partial t} \tag{8}$$

or

$$\frac{\partial T_{(z,t)}}{\partial t} = D\frac{\partial^2 T_{(z,t)}}{\partial z^2} \tag{9}$$

where:

$$D = \frac{k}{\varrho c} \tag{10}$$

In Equation (10), D is the soil thermal diffusivity. In particular, it is associated with the speed of heat diffusion through the vertical profile of the soil. The high magnitude indicates rapid heat conduction and, consequently, the heating and cooling process becomes faster. This is a determinant of soil temperature, and, therefore, different methods have been proposed in the literature to estimate it [18,19]. Among other factors, it is a function of soil constitution, granulometry, density, and structure [20].

2.2. Mathematical Model

Equation (9) presents as a solution the function that satisfies it and, from this, the temperature can be estimated for a given time (t) and depth (z). To obtain the variable, the separation procedure is used:

$$T_{(z,\,t)} = g_{(z)} f_{(t)} \tag{11}$$

Thus, it can be rewritten as follows:

$$\frac{\partial g_{(z)} f_{(t)}}{\partial t} = D \frac{\partial^2 g_{(z)} f_{(t)}}{\partial z^2} \tag{12}$$

Performing the division by $g_{(z)} f_{(t)}$:

$$\frac{1}{f_{(t)}} \left(\frac{\partial f_{(t)}}{\partial t} \right) = \frac{1}{g_{(z)}} \left(D \frac{\partial^2 g_{(z)}}{\partial z^2} \right) \tag{13}$$

Therefore, it is verified that the left (right) end is a function only of time (depth). For equality to be valid, one must consider that the ends are equal to a constant (by convention, equal to $i\omega$). Thus:

$$\frac{\partial^2 g_{(z)}}{\partial z^2} - \frac{i\omega}{D} g_{(z)} = 0 \tag{14}$$

and

$$\frac{\partial f_{(t)}}{\partial t} - i\omega f_{(t)} = 0 \tag{15}$$

Solving Equations (14) and (15):

$$g_{(z)} = c_1 e^{\left(\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} + c_2 e^{\left(-\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} \tag{16}$$

and

$$f_{(t)} = c_3 e^{(i\omega t)} \tag{17}$$

Substituting Equations (16) and (17) in (11):

$$T_{(z,\, t)} = c_3 e^{(i\omega t)} \left(c_1 e^{\left(\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} + c_2 e^{\left(-\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} \right) \tag{18}$$

or

$$T_{(z,\, t)} = e^{(i\omega t)} \left(A e^{\left(\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} + B e^{\left(-\frac{(1+i)}{\sqrt{2}} \sqrt{\frac{\omega}{D}}\, z\right)} \right) \tag{19}$$

The temperature for a theoretically infinite depth does not vary with time and, in turn, must be equal to an average value (mathematically, this means that $T(\infty, t) = \overline{T}$) [21]. The positive exponential diverges when the depth tends to "infinity"; therefore, it becomes necessary to consider $A = 0$. The negative exponential converges when the depth tends to "infinity" and, therefore, it becomes necessary to add a constant ($\overline{T}$) in Equation (19). This can be rewritten as follows:

$$T_{(z,t)} = \overline{T} + B e^{\left(-z\sqrt{\frac{\omega}{2D}}\right)} e^{i\left(\omega t - z\sqrt{\frac{\omega}{2D}}\right)} \tag{20}$$

The temperature for the soil surface ($z = 0$):

$$T_{(0,t)} = \overline{T} + (\alpha - \beta CC) \sin(\omega t + \varnothing) \tag{21}$$

In Equation (21), CC is the cloud cover, and α and β are the constants obtained from the simple linear fit used in the dispersion between the cloud cover and the thermal amplitude for the soil surface. The boundary condition is different from that proposed in [21] and, in particular, stands out by inserting a term that refers to cloud cover. By convention, the following equality can be assumed:

$$B = -i(\alpha - \beta CC) e^{(i\varnothing)} \tag{22}$$

Thus:

$$T_{(z,\,t)} = \bar{T} - i(\alpha - \beta CC)e^{\left(-z\sqrt{\frac{\omega}{2D}}\right)}e^{i\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \varnothing\right)} \quad (23)$$

The soil temperature is a real amount and, therefore, it is necessary to disregard the term involving the cosine. Thus:

$$T_{(z,t)} = \bar{T} + (\alpha - \beta CC)e^{\left(-z\sqrt{\frac{\omega}{2D}}\right)} \sin\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \varnothing\right) \quad (24)$$

In Equation (24), $T_{(z,t)}$ is the temperature for a given depth (z) and time (t), $\bar{T}$ is the average surface temperature (as well as for the entire vertical profile), ω is the angular rotation speed of the Earth (its value, when the argument of the sine function is expressed in radians, is equal to $7.27 \times 10^{-5}\ s^{-1}$), and Ø is the phase constant. Therefore, the temperature varies exponentially with depth (z) and sinusoidally with time (t) and depth (z). In addition, cloud cover will reduce the daily thermal amplitude of the soil (Γ). This can be expressed as follows:

$$\Gamma = (\alpha - \beta CC)e^{\left(-z\sqrt{\frac{\omega}{2D}}\right)} \quad (25)$$

The solution of any differential equation is a function that will satisfy it [22]. In this context, Equation (24) can be derived partially concerning time and twice with respect to depth. Thus, it is obtained that:

$$\frac{\partial T_{(z,t)}}{\partial t} = \Gamma\omega \cos\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \phi\right) \quad (26)$$

and

$$\frac{\partial^2 T_{(z,t)}}{\partial z^2} = \Gamma\left(\frac{\omega}{D}\right) \cos\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \phi\right) \quad (27)$$

Substituting them in Equation (9):

$$\Gamma\omega \cos\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \phi\right) = \Gamma\omega \cos\left(\omega t - z\sqrt{\frac{\omega}{2D}} + \phi\right) \quad (28)$$

Once satisfied, Equation (24) is actually a possible solution. Thus, it can be widely used to estimate the soil temperature for a given time (t) and depth (z).

Finally, for the specific case of the surface, the constants (α and β) enable the analysis of the thermal amplitude for the “clear sky” and “overcast sky” conditions. The “clear sky” provides the minimum values of CC and, in the specific case of becoming equal to 0, the maximum value of the thermal amplitude is obtained ($\Gamma_{max} = \alpha$). The “overcast sky” provides the maximum values of CC and, in the specific case of becoming equal to 1, the minimum value of the thermal amplitude is obtained ($\Gamma_{min} = \alpha - \beta$). Cloud cover can significantly reduce thermal amplitude, and, because they have specific thermal properties, the different types of soils should be analyzed.

2.3. Phase Constant

The daily thermal cycle is characterized by daytime heating (maximum temperatures) and nighttime cooling (minimum temperatures). For the “clear sky” condition (CC = 0), the surface temperature will reach a maximum magnitude at a certain time (t). At this time, the temperature can be expressed as follows:

$$T_{(0,\,t)} = \bar{T} + \alpha \quad (29)$$

In addition, it can be assumed that the maximum magnitude occurs at 1:00 p.m. [23–25]. In this context, Equation (24) can be rewritten for the surface (z = 0):

$$T_{(0,13)} = \bar{T} + \alpha \sin(13\omega + \varnothing) \tag{30}$$

Equations (29) and (30) are analogous so that:

$$\bar{T} + \alpha = \bar{T} + \alpha \sin(13\omega + \varnothing) \tag{31}$$

Thus:

$$\sin(13\omega + \varnothing) = 1 \tag{32}$$

Therefore:

$$13\omega + \varnothing = \frac{\pi}{2} \tag{33}$$

Finally, the phase constant is obtained:

$$\varnothing = -\frac{7\pi}{12} \tag{34}$$

Substituting it in Equation (24):

$$T_{(z,t)} = \bar{T} + (\alpha - \beta CC)e^{\left(-z\sqrt{\frac{\omega}{2D}}\right)} \sin\left(\omega t - z\sqrt{\frac{\omega}{2D}} - \frac{7\pi}{12}\right) \tag{35}$$

This should be used to estimate the soil temperature for a given time (t) and depth (z).

3. Model Results

The models should be employed to verify the divergences and similarities. It is essential to highlight that the "input variables" are characteristic of a Regolithic Neosol ($\bar{T} = 25\ ^\circ C$; $T_o = 10\ ^\circ C$; $D = 2 \times 10^{-6}\ m^2\ s^{-1}$; $\alpha = 10\ ^\circ C$; $\beta = 5\ ^\circ C$) and, particularly, maximum temperatures occur around 1:00 p.m. [26]. Models are employed for two specific/representative moments of the daily cycle to facilitate the analysis, thereby observing the 12-h interval: 1:00 a.m. (nighttime period) and 1:00 p.m. (daytime period). Finally, soil temperatures are presented as a function of cloud cover (*x*-axis) and depth (*y*-axis):

In Figure 2, the models indicate a gradual increase in temperatures with depth. In particular, surface cooling occurs due to the emission of thermal radiation. The soil temperatures remain constant in Figure 2A and, in contrast, increase with cloud cover in Figure 2B. The cloud cover acts as an agent that "imprisons" thermal radiation [12] and, consequently, promotes the heating observed during the nighttime. The heating is more significant near the surface, becoming almost inexpressible from a depth of 0.20 m.

In Figure 3, the models indicate a gradual reduction in temperatures with depth. In particular, surface heating occurs due to the incidence of solar radiation. The soil temperatures remain constant in Figure 3A and, in contrast, decrease with cloud cover in Figure 3B. The cloud cover acts as an agent that "bars" solar radiation [12] and, consequently, promotes the cooling observed during the daytime. The cooling is more significant near the surface, becoming almost inexpressible from a depth of 0.20 m.

These results agree with those obtained for air temperature [27,28]. According to [28], cloud cover can reduce (elevate) the maximum (minimum) air temperatures. Therefore, it intervenes strongly in damping the air thermal amplitude. In this context, the reformulated model is in agreement since the insertion of the term occurred in the one referring to the soil thermal amplitude. Furthermore, the reformulated model indicates the most expressive damping near the surface, becoming irrelevant from the depth of 0.20 m. This depth can be considered the transition between small/large variations in soil temperature [7] and, from the results, the limit for the relationship between the variables.

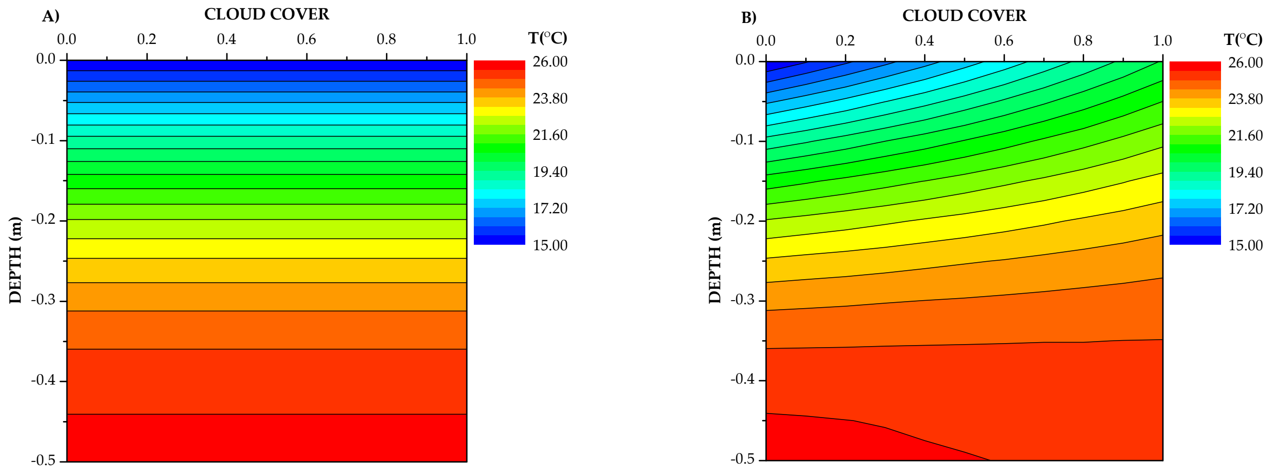

Figure 2. Soil temperature estimated by the conventional (**A**) and reformulated (**B**) models for a specific hour of the nighttime period: 1:00 a.m.

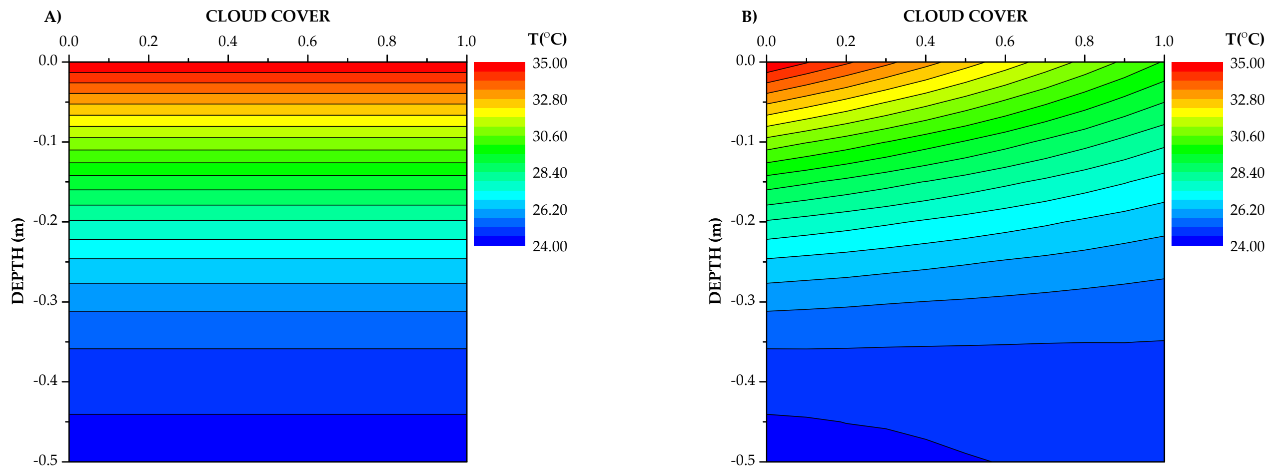

Figure 3. Soil temperature estimated by the conventional (**A**) and reformulated (**B**) models for a specific hour of the daytime period: 1:00 p.m.

According to [28], cloud cover intervenes more significantly to reduce the maximum air temperatures. In particular, it differs from those obtained in the analysis of maximum/minimum soil temperature over China [29]. According to [29], cloud cover has a strong positive effect on minimum soil surface temperature (i.e., increasing magnitudes). Therefore, there is a statistically significant correlation coefficient between such variables—cloud cover and nighttime soil surface temperature. Finally, the reformulated model should be employed to daytime/nighttime periods, thereby contributing to precision agriculture (primarily when the crop development is directly related to soil temperature).

4. Conclusions

The model is reformulated by inserting a variable referent to cloud cover and, in turn, aims to satisfactorily estimate the soil thermal behavior (in particular, on "overcast sky" days). The soil–atmosphere relationship can be slightly altered according to soil thermal properties. Therefore, studies should be realized for different soil types and, besides analyzing the existing relationship, obtain the necessary calibration for the reformulated model. Cloud cover is determinant for the planet's energy balance and, consequently, a significant relationship independent of soil type.

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