Long Wave Radiation Regime in Vegetation-Parameterisations for Climate Research

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Abstract.

An analytical and mathematical model that describe the long wave radiation regime inside a vegetation canopy was developed. The model assumptions are: leaves are the only vegetation elements and are arranged in horizontally infinite layers; they are evenly spread in the layers; having random azimuthal direction and defined zenithal direction. Leaves absorb all thermal radiation, do not scatter any and emit isotropic radiation. An adaptation of the 'View factor' concept describes radiation exchanges between leaves and leaf layers.

The model calculates the amount of irradiance incident on a single tilted leaf from a flat surface (like the ground). It was found that for an isothermal and infinite emitting surface, with both sides of the leaf absorbing identically, the leaf's tilt angle does not influence the amount of irradiance impinging on it. Then the amount of radiation exchanged by two leaves in nearby layers and the irradiance reaching the leaf from a near by leaf layer are evaluated. Next, the 'layer attenuation coefficient', and the 'emission coefficient of a leaf layer' are calculated. Finally, the plane parallel radiation transfer equation of thermal fluxes radiance in vegetation canopy is presented.

It was concluded that for an infinite, homogeneous and isothermal leaf canopy with erect leaves, outside irradiance penetrates into deeper layers and less thermal radiation is released to the surroundings, than for the plane leaf canopy case. From this point of view an erect leaf canopy is better suited to cold climates.

1. INTRODUCTION.

The possible impact of reduction in the earth vegetation cover, has attracted the scientific communities attention and underlined the need to study in more detail the interactions between vegetation and its surroundings. The purpose of this article is to present an analytical model of long wave radiation (LWR) regime inside a vegetation canopy, as part of a better description, of the energy budget in the Earth's lower boundary layer. Further developments of this model may be incorporated into climate simulations. It describes the LWR transfer equation inside canopies and the exchange of thermal radiation fluxes (irradiances) between canopy, ground, and atmosphere. The model deals explicitly with the leaves' location and the relative sizes of leaves and canopy. It fully takes into consideration the mutual shading caused by leaves.

The short wave radiation (SWR) regime in a plant canopy has been described by Ross (1981), Asrar, (1989) and others. Simulation models of the SWR regime within vegetation have been describe by Borel et al. (1991), Govaerts (1996). Field experiments of the SWR in vegetation have been carried out by Ross (1981), Cohen (1983). Short and long wave radiation regime in canopy need to be described differently as the long wave optical properties of vegetation, in the range of 4.0 to 100µm, differ significantly from those in the short wave band. The sources of radiation are also different: while in the SWR most of the radiation comes directly from the sun as a parallel beam, the LWR is incident diffusely from the sky and the ground; and a significant part is due to emission from within the plants by the vegetation elements themselves.

The interaction of radiation with vegetation elements is different from those with gases and aerosols in the atmosphere due to the sizes of those elements in relation to the wave length. As a result, two different new aspects arise- first, the radiation interaction depends not only on the incoming and the outgoing beam directions, but also on the orientation of the canopy elements. And mutual shading between the vegetation elements has to be considered.

Describing the plant architecture is an essential step in modeling the radiation regime. This mean the development of an explicit mathematical formulation of the shape of the canopy, the arrangement of elements (i.e. leaves, flowers, branches, etc.) within it and their shape. In the plant kingdom the variety of the arrangements is so wide that simplifying assumptions must be made. The assumptions in the model are: the interaction of radiation with a canopy is effected only by leaves; the leaves have a known zenith angle distribution and an isotropic azimuth angle one; and the leaves in the canopy are arranged in homogeneous, plane parallel layers (Lemeur and Bland 1974, Goudriaan 1977, Asrar 1989, Kimes et al. 1981).

To the best of our knowledge, no field experiments have simultaneously measured the LWR regime inside vegetation canopy, the incoming LWR and the parameters of the vegetation canopy. So at this stage, model confirmation could not be carried out.

2. FUNDAMENTALS OF THERMAL RADIATION TRANSFER IN VEGETATION CANOPIES.

More then 30% of the total energy released from the Earth's surface to the atmosphere above is in the form of long wave radiation. It is found in many climate models, that doubling the CO_2 air concentration from its present level, would lower the amount of LWR emitted by the Earth to space by 4 Wm^{-2} (Wielicki et al., 1995). In moderate climate regions, 4 Wm^{-2} is around 1% of the average thermal radiation emitted from surfaces. According to Otterman et al. (1995), the range of emitted LWR from different vegetation covers is larger than 1%. Since close to 40% of the Earth's land surface is covered by vegetation, it is important to look into thermal radiation in canopies more closely.

Miller (1981) presented measurements of short and long wave irradiance at a grass surface. The average all day- long wave irradiance is almost 40% of the total net radiation. The net long wave radiation at midnight is around 50% of that at noon. Throughout the night, and in some hours of the day time, LWR is the major component of the radiation exchanged between the vegetation and the atmosphere. Thermal radiation is important to plant development.

The atmospheric thermal radiation depends on weather conditions (Gates, 1980). Regarding soil as a gray body, the emission from the ground can be evaluated using Stefen-Boltzman's law. The flux depends on the soil temperature and on its LWR emissivity coefficient, which, in turn, depends strongly on the kind of soil, and shows only weak dependence on the wave length. Approximately 80% of the emitted radiation from soil is Lambertian (Lagouade et al, 1995).

Leaf temperature is the result of the over-all leaf energy balance, which is mainly the sum of the net sensible and latent heat exchange with the ambient air, and the net radiation, short and long wave, exchanged (photosynthesis and heat capacity are neglected). Models of the energy balance between canopy and the surroundings have been constructed by Choudhury and Monteith, (1988), and others.

Information on the IR optical properties of vegetation elements is limited. They are usually considered as being close to black body emitters, the radiation depending mainly on the leaves temperature. The leaf emissivity coefficient varies in the range of 0.94 - 0.99, according to the plant type. Little information exists on the leaf emissivity's angle and wave length dependencies (Lagouarde et al. 1995). The available data lead to the assumptions that the emissivity is independent of wave length and the emitted radiation is isotropic, obeying Lambert's law. It is common to consider the LWR leaf reflection coefficient to be about 0.05 and to assume that no transmission exists. As a result, Ross (1981) ignores the scattering term in the transfer equation of thermal radiation inside vegetation. The emitted LWR from leaves is given by the Stefen-Boltzman law.

The IR optical properties of a plant canopy differ from those of a single leaf. The canopy emissivity is greater than the leaf emissivity (Boissard et al. 1990); the canopy emissivity is anisotropy, and so does not obey Lambert's law. The anisotropy of emitted thermal radiation from canopies is due to a combination of different amounts of ground cover by vegetation elements, the architecture of the canopy and the fact that elements are at different temperatures (Paw U, 1991).

3. MODEL OF IR RADIATIVE TRANSFER IN VEGETATION CANOPY.

3.1. Absorption of Long Wave Radiation Emitted from a Flat Surface by a Leaf.

The ground below a leaf or the atmosphere above it, can be treated as infinite flat surfaces. The question addressed below is how much radiation a small flat single leaf in space receives from an emitting surface.

By using the 'view factor' methods, the amount of thermal radiation which is emitted from the ground surface area, A_2, and incident on a leaf element surface dA_1 can be expressed as, (Modest, 1993):

$$(1)\quad F_{A_2 \to dA_1} = dA_1 \int_{A_2} I(R,\varphi)\frac{\cos\vartheta_1 \cos\vartheta_2}{r^2} dA_2$$

where: $F_{A_2 \to dA_1}$ - the density of radiation (irradiance) that comes to the leaf from an area A_2 on the ground.

$I(R,\varphi)$ - the perpendicular emitted radiance from a unit area of ground surface, located at a distance R and at an angle φ (Fig. 1).

r - the distance between the two surfaces. and,

ϑ_1 and ϑ_2 - the angles between the radiation beam and the perpendicular to the leaf and the ground surfaces, respectively.

It can usually be assumed that a ground area around a leaf, large in area compared to the latter, is composed of the same material and receives the same amount of SWR from above. That implies that the underlying soil has locally homogeneous temperature and optical properties. Accordingly, the emitted radiance - I, is independent of the ground location. With the help of Fig. 1, the geometry for calculation of the irradiance a leaf received from an infinite surface is shown.

The connection between the angle ϑ_1^2 and α, ϑ_1^1 and φ is:

(2)

$$\cos\vartheta_1^2 = \cos\alpha \cos\left(\alpha + \vartheta_1^1\right) + \sin\alpha \sin\left(\alpha + \vartheta_1^1\right)\cos\varphi$$

where:

$$(3)\ \cos\vartheta_2 = \frac{H}{\sqrt{H^2+R^2}}\ ,\ (4).\ \sin\vartheta_2 = \frac{R}{\sqrt{H^2+R^2}}$$

By substituting equation 2 instead of $\cos\vartheta_1$ into equation 1, and using equations 3 and 4, the 'view factor' between emitted unit area and a receiving leaf's unit area is equal to:

(5)

$$df = \left[\frac{1}{\left(H^2+R^2\right)}\right]^2 \left[H^2 \cos\alpha + RH \sin\alpha \cos\varphi\right] R d\varphi dR$$

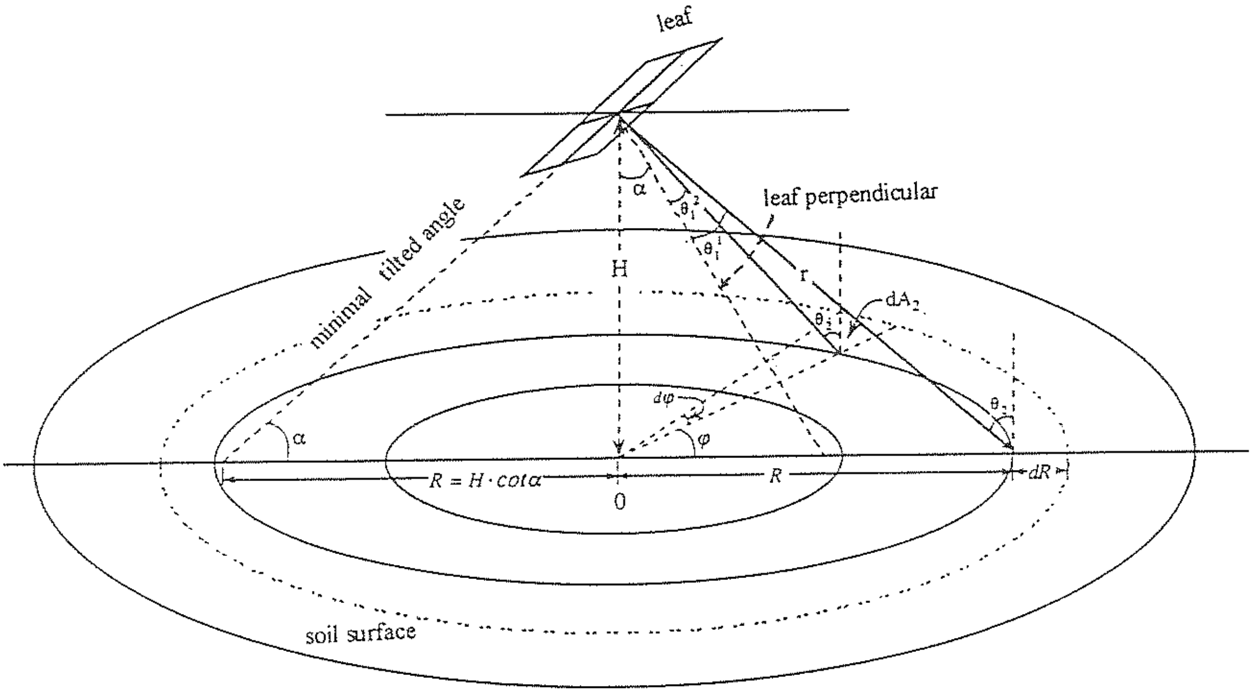

Figure 1: Schematic representation of the variables expressing the radiation received on a leaf surface, when emitted from an infinite plane.

where: H - leaf's height above the surface.

ϑ_i^1 - the angle between the leaf perpendicular and a beam that comes from radius R for $\varphi_1 = 0$.

ϑ_i^2 - the angle between the leaf perpendicular and a beam that comes from any point on radius R.

r - the distance $r = \sqrt{R^2 + H^2}$.

α - the leaf tilted (inclination) angle.

φ_1 - the angle on the ground surface between the directions line and an emitted element.

The irradiance, F, the leaf will receive from all of the emitting surface is:

(6)

$$F = \int df = \iint_{R\varphi} I(R,\varphi)\frac{H}{\left(H^2+R^2\right)^2}\left[RH\cos\alpha + R^2\sin\alpha\cos\varphi\right]d\varphi dR$$

The solution of eq. 6 with the above condition shows that the irradiance a leaf receives from an infinite emitting surface is equal to π (where $I = 1$). Monteith (1973) has shown that the irradiance on a tilted surface coming from an isotropic arch is also equal to π. The meaning is that the irradiance a single leaf (not shaded by other leaves) receives from a surface is independent of the leaf tilt angle.

3. 2. The Irradiance From an Emitting Layer to a Leaf Above.

The irradiance incident on a leaf from a layer made of small emitting surfaces (leaves), in the plane leaf case ($\alpha = 0$), has a solution similar to that of a continuous infinite emitting plane surface as presented above, that is $\pi \cdot LAI(i)$ where $LAI(i)$ is layer i's leaf area density.

In a canopy where the leaves are tilted, the situation is more complicated. Due to leaves' mutual shading, the radiation from an emitting layer is divided into two regions: the region close to the receiving leaf where disturbance of emitted radiation can be neglected, and the irradiance from the outer region where mutual shading has to be considered. In reality, mutual shading of-course increases gradually. The irradiance, $F_{\Re}$, a leaf receives from the inner region, defined by the "shading radius" - $\Re$, is approximately:

(7) $$F_{\Re} \cong \frac{LAI}{\pi} \cdot ln\left(\Re^2 / h^2\right)$$

To calculate the radiation emerging from outside the region of radius $\Re$, where shading does occur, the emitting leaves are arranged in concentric rings around a center, located exactly below the receiving leaf, as shown in Fig. 2. These concentric rings are titled 'leaf fences', and are formed from leaves that have been 'moved' from the area within two adjacent fences to the distant one. The distance between two adjacent 'leaves fences' is minimal, allowing radiation emitting from the bottom of the distant fence to reach the lower part of the receiving leaf above.

The irradiance on an erect leaf $(\alpha = \pi/2)$ from leaves located outside radius $\Re$ - $F_{\Re \to \infty}$, arranged in fences, is:

$$F_{\Re \to \infty} = 2\pi \cdot \frac{(h-a)}{\Re} \quad (8)$$

The total irradiance, F, a single erect leaf receives from an isothermal layer of erect leaves, is calculated as the sum of eq. 7 (where the *LAI* is express in terms of the layer density parameters - A, a and h) and eq. 8. Considering I = 1 at all points in the emitting layer, that irradiance is:

$$F = \frac{2 \cdot a^2}{\pi A^2} ln\left(\Re/_{h}\right) + 2\pi \cdot \frac{(h-a)}{\Re} \quad (9)$$

The irradiance incident on a leaf according to eq. 9, exceeds that on a plane leaf above a layer of plane leaves, if both layers have the same parameters. Mutual shading is due also to shading caused by leaves in the receiving leaf layer. That calculation, has been carried out and is presented elsewhere (Rotenberg, 1997).

In the coming section the plane parallel transfer equation of the long wave irradiance through the vegetation canopy is presented

3.3. Equation of Long Wave Radiation Transfer in Vegetation Canopy.

Let us first show the parameters of the equation. The LWR transfer equation is shown in two cases: a canopy of plane leaves $(\alpha = 0)$; and a canopy of erect leaves $(\alpha = \pi/2)$.

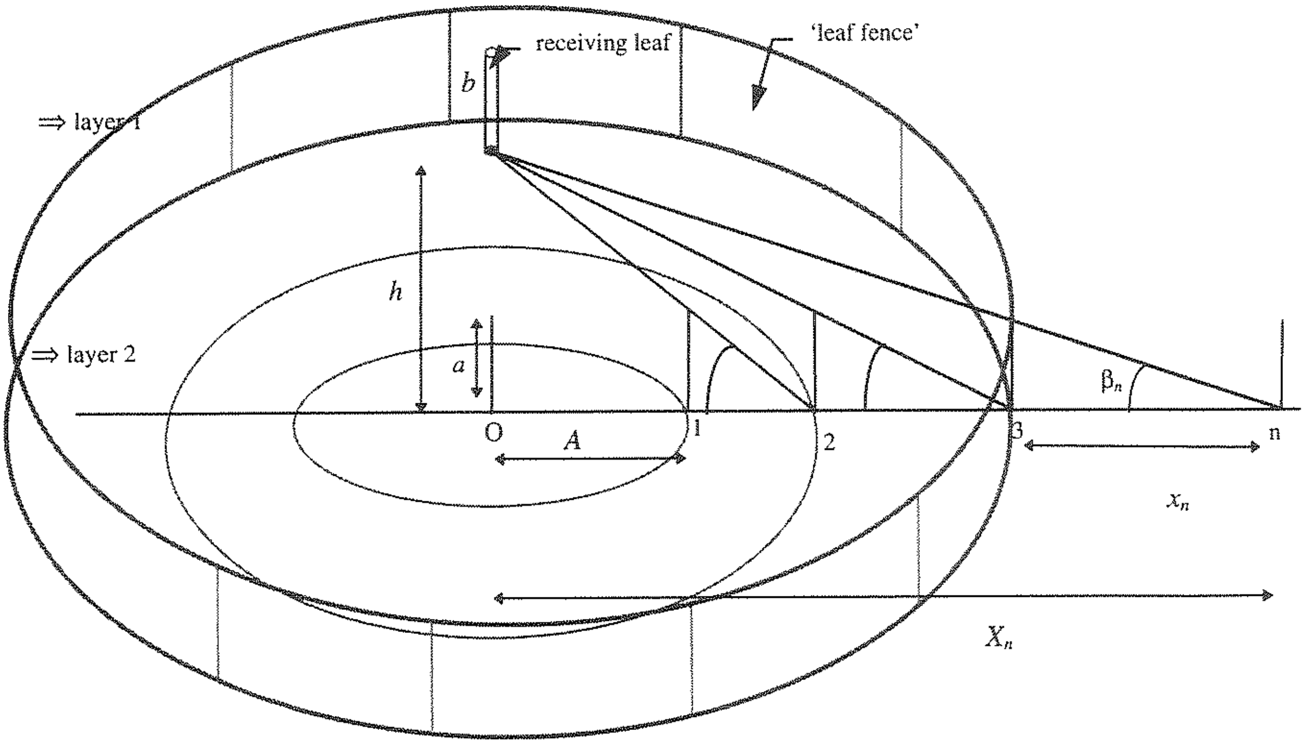

Figure. 2: Schematic presentation of the radiation arriving on a single leaf from a layer of leaves below. The rings represent the leaves which are exposed completely to the leaf above.

where: a - the average height of leaf.
h - distance between two adjacent layers.
X_n - distance between the n fence to the center.
β_n - the angle connected the bottom of the n fence to the receiving leaf above.
A - average distance between two adjacent leaves in a layer.
x_n - distance between two adjacent 'leaves fences'.

Any radiation incident on leaves is ultimately re-emitted and in the long wave range it is assumed that leaves absorbed all incident radiation (Ross, 1981). Therefore, a bi-layer 'leaf layer attenuation coefficient', $\kappa^*_{LWR(2\to1)}$, may be derived from the values of F calculated in sections 3.1 and 3.2. Thus in a canopy of tilted leaves, this coefficient depends on the tilt angles (α_1 for the receiver layer and α_2 for the emitter layer), and the layers' *LAI* (which are functions of: *a*, *A* and *h*.). It is equal to:

(10)
$$\kappa^*_{LWR(2\to1)}(\alpha_1,\alpha_2,LAI(i_1),LAI(i_2)) = LAI(i_1)\cdot F\left(i_{(2\to1)}\right)$$

where: $F\left(i_{(2\to1)}\right)$ is the view factor between an emitted layer area (2) and an element area in the receiver layer 1.

In a canopy of plane leaves, in which all leaves in the layer are situated in the vertical middle, mutual shading does not exist, neither in the emitting nor in the receiving layer. Using the result of section 3.1, one gets that the layer attenuation coefficient is:

$$(10)\quad \kappa^*_{LWR(2\to1)}(\alpha=0) = LAI(i_1)\cdot LAI(i_2)\cdot\pi$$

The layer emission coefficient - E_M.

Assuming the leaves to be grey body emitters, the irradiance, E_L, of a leaf, emits to an hemisphere above, using the Stefen-Boltzman law is:

$$(11)\qquad E_L = \varepsilon\sigma(273+T_L)^4$$

where: ε - the leaf emissivity coefficient. and
T_L - the leaf temperature.

The emission coefficient of a layer of plane leaves to its hemisphere above, is: $E_M(\alpha=0,i) = LAI(i)\cdot E_L$. On the other hand, layer with in tilted leaves, mutual shading has to be considered. Therefore, the emission coefficient for a layer of an erect leaves, is equal to:

$$(12)\quad E_M\left(\alpha=\pi/2,i\right) = LAI(i)\cdot E_L\cdot\left(1-2/\pi\right)$$

The long wave irradiance transfer equation.

The coefficients of the irradiance transfer equation, in a canopy of plane leaves depend on the emitting or the receiving layer only. Hence, use can be made of the well-known turbid medium transfer equation. When the layer temperature is height dependent, the transfer equation for the plane leaf case is equal to:

$$(13)\quad dJ(L)/dL\cdot LAI(L) = -J(L) + E_L(T(L))$$

where: J is the irradiance at height L in the canopy. J replacing I in the turbid medium equation.
$L(i)$ - downward cumulative leaf area index.

In a canopy of tilted leaves, the layer attenuation of irradiance coming from another leaf layer depends on the parameters of both layers. As a result, the upward irradiance on a layer j, from all the layers below it, starting from layer 1 - $J_{Cu,j}$ is:

$$(14)\qquad J_{Cu,j} = \sum_{i=1}^{j-1}\left(\kappa^*_{i\to j}\cdot I_i\right)\cdot\frac{E_{M,i}-J_{i\to j-1}}{E_{M,i}}$$

κ^* is given by eq. 10, E_M by eq. 12, and I_i is the radiation of layer i.

Eq. 14 present the change of irradiance in the canopy layers due to leaves emission. The equation has to be solved numerically. On the other hand, the layer attenuation for irradiance arriving from the surroundings, depend only on the layer. Equation similar to eq. 13, with out the emission term, present the penetration of that irradiance. Solving that equation together with eq. 14 presents the irradiance regime inside erect leaf canopy.

4. CONCLUSIONS.

1) The plane parallel transfer equation for long wave irradiance in vegetation canopy has been presented in this paper. It is a function of the layer density parameters: *a*, *A*, and *h*; the representative leaf layer temperature *T*, and the leaves' tilt angle α. It is presented in terms of exchange coefficients between layers, analogously to the "exchange between layers" or "exchange to space" formulations in the turbid case for gaseous atmospheres, used in Climate models.

To our best knowledge, it is the first model which describe the thermal irradiance regime analytically in a medium composed of small flat elements, arranged in layers, with size much larger than the wave length. It is also the first model which is not based on the turbid or semi-turbid assumptions.

2) Layer attenuation coefficient and emission coefficients have been defined.

3) Additional results also emerge from the present model:

a. The irradiance incident on a single leaf, emerging from an horizontally, infinite, isothermal and diffused surface, does not depend on the leaf tilt angle.
b. The irradiance on a leaf from an isothermal horizontally infinite leaf layer, depends on: the layer' density parameters, on the leaves tilt angle and on the distance between the layers.
c. A single erect leaf, is exposed to higher irradiance from an adjacent erect leaf layer, than that incident on a plane leaf from an adjacent plane leaf layer, if the other parameters are the same.

4) The above results leads to the conclusion that an infinite homogeneous canopy of erect leaves, emits less thermal irradiance to the surroundings than a plane leaf one do. Irradiance incident from outside can penetrate deeper into such canopies. Also the leaf temperature is more homogenous in that canopy. As a result it is expected that the temperature of an erectophile leaf canopy will be warmer than that of a planophile one, under similar conditions. This

may mean that an erectophile leaf canopy is more suitable to cold climates.

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