S1 On the parameterization of radiation as it interacts with canopies

A concise description of the incoming solar radiation reaching plants is an essential ingredient for any transpiration model. A treatment of radiation that is suitable for hydrological models without introducing unnecessary complexities can be found in Corripio (2003).

Assuming that $R\downarrow_s$ is the total downwelling, incoming, shortwave radiation and $R\downarrow_l$ is the total downwelling, longwave radiation, then:

$$R_i \downarrow = R_i^A + R_i^R + R_i^T \tag{S1}$$

for $i \in \{s, l\}$ where the superscript A means absorbed, R is for reflected and T is for transmitted. Of the three components, only the absorbed radiation contributes to the energy budget of the canopy. Usually, it is posed that $R_i^R = \alpha R \downarrow_i$, where α is the albedo, while R_i^T is estimated through variations of the Lambert-Beer law, as described, for instance, in de Pury (1995), Chapter 6, Section 6.2.3.2.

The theory of how radiation impacts canopies goes back to Monsi and Saeki (1953) and is best summarized in Goudriaan (1977) and Hirose (2004). In the seminal papers canopies are treated as an oriented continuums, the direction of which is given by the sun beam downward into the canopy. In this case, the cumulative amount of leaves going deeper and deeper into the canopy can serve as a coordinate with values that go from 0 at the top of the canopy to L_c, the total leaf area index (LAI), at the bottom of the canopy.

Even though very complex and detailed models of canopies can be envisioned, an often-used, idealized compromise is the sun-shade model, in which all the complexity of the canopy is reduced to two ideal layers: one layer of leaves that are directly sunlit and the other of leaves that are shaded. Besides, part of the radiation can pass through the canopy and hit the soil. As shown in Figure S1, the two layers really are more conceptual than geometrical, since in reality the set of sunlit leaves can be quite sparse and spread deep into the canopy, depending on leaf distribution and orientation.

The sun-shade model first estimates the penetrating solar beam (direct light) per unit ground area $R_b(L)$, which decreases in accordance with a Lambert-Beer type law (as taken from de Pury (1995), Chapter 6.2):

$$R_b(L) = R_b(0)e^{-k_b L \Omega} \tag{S2}$$

where $R_b(0)$ is the direct solar radiation on top of the canopy, k_b is a beam radiation extinction coefficient of canopy, function of the solar elevation angle, and Ω is a correction factor, called the clumped canopy coefficient, that has been introduced in recent papers such as Ryu et al. (2011) to account for the distribution of leaves. This "sunfleck" contribution is represented in Figure S1 by the orange beams hitting and passing through part of the canopy.

The determination of the absorption of all light fluxes per unit leaf area is based on the alteration in radiation with depth, expressed mathematically as the first differential. The impact of leaf absorption is contingent upon whether scattering is integrated into the flux or treated as a distinct component. In cases where a flux excludes scattering, the absorbed light undergoes further reduction due to the absorptivity of the leaves, denoted as $(1 - \sigma_c)$, where σ_c represents the leaf scattering coefficient. Conversely, when the flux is a net flux that already encompasses canopy reflectance and scattering, the calculation of absorbed light is simply derived from the differential.

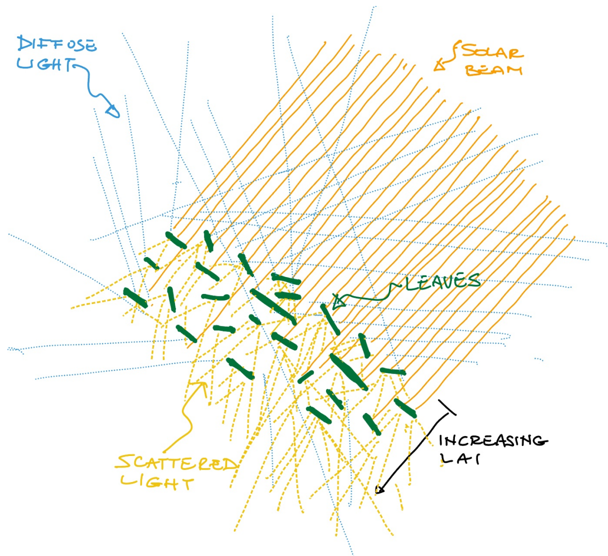

Figure S1: Schematic representation of a portion of a canopy being struck by a solar beam. The canopy is represented by the set of green segments, the incoming sunlit is depicted in orange, the light scattered by the leaves in yellow, and the diffuse atmospheric light in light blue.

Considering only direct beam sunlight, the average beam sunlight absorbed per unit leaf area ($R'_{Sun}(L)$) is calculated by the first differential of Eq. S2 by the leaf absorptivity:

$$R'_b(L) = (1 - \sigma_c)\Omega k_b R_b(0) e^{-k_b L \Omega} \tag{S3}$$

which represents the sunlight absorbed by a layer of leaves between the levels $[L_{AI}, L_{AI} + dL_{AI}]$. The fraction of leaves in sunfleacks, f_{Sun}, is derived from the beam penetration function:

$$f_{Sun}(L) = e^{-k_b L \Omega} \tag{S4}$$

The radiation absorbed by the sunlit leaf fraction of the canopy $R_{Sun}(L_c)$ is calculated as the integral of the absorbed radiation over the L_c and the sunlit leaf area fraction:

$$R_{Sun}(L_c) = \int_0^{L_c} R'_b(L) f_{Sun}(L) dL = R_b(0)(1 - \sigma_c)(1 - e^{-k_b L_c \Omega}) \tag{S5}$$

Similar treatments to the one used to derive Eq. S5 are reserved for the scattered and diffuse light, represented in Figure S1 by the blue and dark yellow dashed lines. Unlike the direct beam, scattered light and diffuse light are thought to be isotropic from all directions. The details of the calculations can be found in Section 6.2 of de Pury (1995), with slightly different notation then that used here.

Although direct light and diffuse light are usually considered separately, the scattered light component is dealt with together with the other two, as in equations (2) to (11) in Ryu et al. (2011), ensuring that all the direct shortwave radiation, not only the photosynthetic active radiation (PAR), is included so that the energy budget is considered in its completeness. The leaves in shade are hit by scattered and diffuse light but also by the radiation reflected by the soil (Ryu et al., 2011). Finally, radiation is subdivided into its longwave and shortwave components, as is quantified in equations (12) to (21) in Ryu et al. (2011). Overall we have at least 10 different components of radiation. However, they still do not contain the radiative feedbacks, which are essential in stabilizing leaf temperature. Any layer, because its temperature, emits a quantity of radiation:

$$R_{f_j} = -2\epsilon\sigma T_i^4 \tag{S6}$$

where $j = \{sun, shade\}$ and $i = \{shade, sun\}$, and the same layer receives from the other layer an amount of radiation:

$$R_{f_i} = \epsilon\sigma T_j^4 \tag{S7}$$

with the subscripts exchanged. Eq. S6 is thought equally likely to be shared between other parts of the canopy and the external environment. Therefore each conceptual layer is receiving a radiation quantity from any other layer as in Eq. S7.

Finally, with a sun-shade model the residual radiation hits the terrain and is partially reflected back, and, as mentioned before, this reflected radiation is added back to the shaded compartment of the model.

S2 Stomatal Conductance Functions

While there are many stomatal conductance functions in literature that could be considered, here we present in more detail only two: the Jarvis parameterization (Jarvis et al., 1976), expecially the one proposed by White et al. (1999) and by Macfarlane et al. (2004), and a second interesting function proposed by Ball-Berry-Leuning (BBL) (Ball et al., 1987; Leuning, 1990; Dewar, 2002).

S2.1 The Jarvis-type stress parameterization

The Jarvis stress factor is a concept used in modeling the stomatal conductance of plants under different water stress conditions. It is based on the Jarvis model which incorporates various environmental factors to estimate stomatal conductance. Several studies have explored the performance of different water stress indicators in the Jarvis model. Yu et al. (2017) compared three indicators: soil water content, J_S; leaf-air temperature difference, J_T; and leaf level water stress index (CWSI_L), J_C. They found that the J_T and J_C models had better simulation accuracy than the J_S model. Wang et al. (2013) developed an improved Jarvis model and found that it had better simulation results compared to the original Jarvis model and an artificial neural network model. These studies highlight, firstly, the importance of considering environmental factors and using appropriate indicators in the Jarvis model to accurately estimate stomatal conductance under water stress conditions, secondly, the variety of studies that have been carried out on the Jarvis model.

Jarvis et al. (1976) introduced some functions to parametrize the stress functions of the model. In literature there are several types of conductance models, however, the environmental stress functions implemented in GEOET model (EvapoTranpiration model of GEOframe), and expacially in the `geoet.stressfactor` package, follow the version of the model proposed by White et al. (1999) and by Macfarlane et al. (2004), where the conductance is equal to:

$$g_s = g_{s,max} \cdot f(R_{PAR}) \cdot f_T(T_a) \cdot f(VPD) \cdot f(\psi_l) \tag{S1}$$

where $g_{s,max}$ is the conductance without any kind of stress and in well-watered conditions [m s^{-1}], while $f(R_{PAR})$, $f_T(T_a)$, $f(VPD)$ and $f(\psi_l)$ are the normalised stress factors, empirical functions with codomain in [0,1], induced respectively by the photosynthetically active radiation (PAR), the air temperature, the water pressure deficit, and the leaf water potential. To simplify, one usually calculates $f(\psi_l)$ as a function of soil water content, denoted as $f(\theta)$.

- **Total solar radiation stress**

According to White et al. (1999), the solar radiation stress can be computed as:

$$f(R_{PAR}) = \left[\frac{1}{2\theta}\left(\alpha R_{sw} + 1 - \sqrt{(\alpha R_{sw} + 1)^2 - 4\theta\alpha R_{sw}}\right)\right]^{-1} \tag{S2}$$

where α and θ are the slope and shape parameters of the stress function $f(R_{PAR})$ and are set equal to 0.005 and 0.85 [-], respectively. R_{sw} is the total solar radiation, expressed in $\mu molm^{-2}s^{-1}$. If we want to express it in Wm^{-2} we must include a conversion factor equal to $\approx \frac{1}{4.6}$.

- **Air temperature stress**

Following Jarvis et al. (1976) and White et al. (1999) the air temperature stress factor can be computed as:

$$f_T(T_a) = b(T_a - T_l)(T_h T_a)^c \tag{S3}$$

where b and c are defined as:

$$c = \frac{T_h - T_0}{T_0 - Tl} \tag{S4}$$

$$b = \frac{1}{(T_0 - Tl)(T_h - T_0)^c} \tag{S5}$$

where T_0 is the temperature at maximum conductance [°C], and T_l and T_h are the lower and upper temperatures of the range for which a positive stomatal conductance is predicted [°C]. White et al. (1999) assigned the values for T_l, T_0 and T_h equal to 0°C, 17°C and 38°C, respectively. These parameters can be set a priori or calibrated.

- **Vapour pressure deficit stress**

The vapor deficit stress factor can be estimated as in White et al. (1999):

$$f(VPD) = 1.1 \exp(-0.63 \cdot VPD) \tag{S6}$$

where VPD is the vapour pressure deficit value and when $VPD = 0.2kPa$, $f(VPD) = 1$.

S2.2 Parameters for the Medlyin Formula

The second type of parameterization for stomatal conductance is due to Ball-Berry-Leuning (BBL) (Ball et al., 1987; Leuning, 1990; Dewar, 2002) and it has been modified in various ways since the original paper. An interesting form of the BBL was obtained in Medlyn et al. (2011), under the hypothesis of optimal photosynthesis theory (Eq. **??**).

Lin et al. (2015) gives values for the g_1 variable for various types of vegetation in different locations, reported in Table S1.

Table S1: Estimates of g_1 by different classification schemes according to Lin et al. (2015).

Classification scheme	Class	g_1 mean	g_1 SE
a_Pathway	C4	1.62	0.03
	C3	4.16	0.01
b_Plantform	Gymno. tree	2.35	0.02
	shrub	3.32	0.05
	Angio. tree	3.97	0.02
	Grass	5.25	0.13
	Savanna tree	5.76	0.22
	Crop	5.79	0.04
c_T region	Artic	2.22	0.07
	Boreal	2.19	0.02
	Temperate	4.31	0.02
	Tropical	4.43	0.08
d_W Region	$MI < 0.5$	3.77	0.03
	$0.5 \leq MI < 1$	4.69	0.04
	$1.0 \leq MI < 1.5$	3.87	0.03
	$MI > 1.5$	4.02	0.02
e_PFTs	C4 grass	1.62	0.03
	Ever.gymno.tree	2.35	0.02
	Deci.savanna. tree	2.98	0.39
	Shrub	3.32	0.05
	Ever. angio. tree	3.37	0.03
	Trop. Rainforest tree	3.77	0.04
	Deci. angio. tree	4.64	0.04
	C3 grass	5.25	0.13
	C3 crop	5.79	0.04
	Ever. savanna tree	7.18	0.25

S3 The Object Modeling System v.3 (OMS3)

The Object Modeling System v.3 (OMS3), a component-based environmental modeling framework introduced by David et al. (2013), offers a cohesive and efficient approach to environmental modeling. OMS3 facilitates the creation of science simulation components, the development, parameterization, and evaluation of environmental models, and the adaptation of these models to evolving scientific advancements and emerging customer needs. In OMS3, the term "component" refers to self-contained software units that implement independent functions within a context-independent structure (David et al., 2013). This approach allows developers and researchers to construct models as compositions of standalone components, moving away from traditional monolithic approaches. The framework underpins the entire GEOframe system.

Contrasted with other Environmental Modeling Frameworks (EMF), OMS3 distinguishes itself as a non-invasive and lightweight framework (Lloyd et al., 2011). The model code remains decoupled from the underlying framework - OMS3, relieving environmental modelers from the necessity of deep API knowledge. Consequently, the modeling components can function and evolve autonomously outside the framework. OMS3 leverages specific annotations to provide metadata for Java code. These annotations describe coding elements such as classes, fields, and methods, enabling the framework to interpret components as fundamental building blocks of modeling solutions. This interpretation controls the connectivity and data flow within the modeling process (David et al., 2013).

Furthermore, adopting a software framework like OMS3 positively impacts "non-functional" quality attributes, including maintainability, portability, reusability, and understandability (David et al., 2013). The component-based approach facilitates problem breakdown into manageable units, each addressed by a dedicated component. The amalgamation of these components constructs the desired modeling solution, enabling the construction of new modeling systems through a plug-in model component system (David et al., 2013; Peckham et al., 2013; Serafin, 2019). The modularity of OMS3 streamlines the incorporation of scientific advances into components without affecting the system's other aspects. Additionally, it fosters the transparent development of code and its long-term sustainability, addressing historical limitations associated with inadequate software architectural design (David et al., 2013; Bancheri, 2017; Formetta et al., 2014a; Rizzoli et al., 2006).

The component-based approach encourages collaborative model development and simplifies the attribution of authorship, as components can be authored independently. Furthermore, OMS3's adoption promotes the concept of reproducible research, facilitating third-party scrutiny and ensuring consistent, verifiable model results (Bancheri, 2017; Formetta et al., 2014a; Serafin, 2019). An additional advantage of utilizing OMS3 lies in its ability to maintain code development transparency for users. This feature ensures accessibility to the underlying code structures and contributes to the framework's effectiveness.

S4 GEOframe system and policy

GEOframe is an open-source[1]. system for designing modeling solutions for semi distributed hydrological modeling. GEOframe is not a model in the classic sense of the term but it is more a system of components that can be joined together at run-time for obtaining "modeling solutions" customized for the application in exam. With the aim of establishing a community that fosters the

[1] All the models of GEOframe on GitHub page: (`https://github.com/geoframecomponents`)

Figure S2: GEOframe organization logo.

sharing of ideas, inquiries, uncertainties, and support, the inception of the GEOframe organization took shape. This organization is envisioned as a hub for computerized hydrology, providing a collaborative platform for researchers and users. Although the concept of this community dates back to 2008, its tangible realization unfolded in 2016, with the logo depicted in Figure S2.

In a modeling system like GEOframe each component represents a physical process and it is constructed as a standalone component that can be connected with the others via the input/output. In this way each user can easily build-up and modify its own set of components and connect it with the rest of the system provided by the work of other PhD students and researchers. This modular approach has demonstrated exceptional versatility and robustness across various applications. Within the GEOframe framework, each segment of the hydrological cycle is represented by a self-contained building block known as an OMS3 component (David et al., 2013). These components can be flexibly combined to create diverse modeling solutions, spanning from simple to intricate tasks.

GEOframe encompasses so many available components, categorized as follows:

- Geomorphic and Digital Elevation Model (DEM) analyses
- Spatial extrapolation/interpolation of meteorological variables
- Estimation of the radiation budget
- Evapotranspiration estimation
- Runoff production estimation using integral distributed models
- Channel routing
- Travel time analysis
- Calibration algorithms

GEOframe involves in its framework several components, each contributing to distinct facets of hydrological modeling. Geomorphic and DEM analyses enable the discretization of the basin into Hydrological Response Units (HRUs), while meteorological forcing data undergoes spatial interpolation using techniques like Kriging (Bancheri et al., 2018). Shortwave and longwave radiation components aid in estimating the radiation budget (Formetta et al., 2013, 2016), and diverse models are employed for evapotranspiration estimation (Bottazzi, 2020; Bottazzi et al., 2021).

Snow melting and runoff production are addressed using specialized models (Formetta et al., 2014b; Bancheri et al., 2020), with the Muskingum-Cunge method employed for channel routing (Bancheri et al., 2020). Travel time analysis of pollutants within the catchment is conducted using the method proposed by Rigon et al. (2016b) and Rigon et al. (2016a). Calibration algorithms are also available, including Let Us CAlibrate (LUCA) (Hay et al., 2006) and Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995).

The process simulations are managed through NET3, a graph-based structure inspired by a river network analogy (Serafin, 2019). Each Hydrological Response Unit (HRU) serves as a node, and channel links are akin to connections between nodes. Different modeling solutions can be implemented within any NET3 node, allowing nodes to be connected or disconnected dynamically through scripting.

GEOframe's open-source nature fosters research reproducibility and replicability (Bancheri, 2017), promoting collaboration, documentation sharing, and archiving of examples and data within the GEOframe community.

S4.1 The GEOframe Community Publication Policy v. 1.0

Below a short summary of the GEOframe Community Publication Policy v. 1.0. For a more comprehensive and detailed understanding, please refer to:

- `https://abouthydrology.blogspot.com/search?q=policy`;
- `https://abouthydrology.blogspot.com/2020/02/about-papers-authorship.html`;

As GEOframe gains increasing popularity, it is essential to establish equitable guidelines for involvement in publications related to GEOframe. While the components are typically distributed under the GPL3 license, which permits extensive code utilization with minimal constraints (primarily centered around maintaining openness and accessibility of derived code), this stipulation is moderated by the possibility of employing diverse licenses for different OMS components. Nonetheless, given that our recognition predominantly stems from publications and correct citations, it is crucial to emphasize the points outlined below.

S4.1.1 Introduction

GEOframe-NewAge stands as an open-source, semi-distributed hydrological modeling system, operating on a component-based framework. Crafted using Java and grounded in the Object Modeling System V3 (OMS3) (Section S3) for environmental modeling, this project's genesis can be traced to Professor Rigon's concept. Its principal development occurred primarily at the Department of Civil, Environmental, and Mechanical Engineering at the University of Trento, Italy. Over the past decade, the GEOframe community has flourished, comprising numerous researchers worldwide. Their collaborative efforts involve sharing code, insights, knowledge, and experiences, all geared toward enhancing the experience of GEOframe users, while simultaneously advancing their individual research pursuits and careers.

In light of this, appropriately acknowledging intellectual contributions through co-authorships or citations is fundamental to the community's harmonious functioning.

S4.1.2 General principles

The current usage terms of GEOframe adhere to the G.P.L. v 3 license, although individual components can have unique licenses. This policy is comprehensive, encompassing all applications of GEOframe products – encompassing data and code – in research and teaching. It doesn't intend to impose limitations on usage, but rather emphasizes proper acknowledgment and communication between users and developers. The policy will undergo periodic updates.

Developers, defined as those who have significantly influenced code design or contributed code, whether scientifically or technically, are encouraged to promptly publish their work. Potential users are advised to engage with developers early on to prevent redundant efforts. Developers retain the right to the first scientific application of their scheme and can guide when co-authorship, citation, or acknowledgment is fitting. The GEOframe website will maintain a record of new developments and the responsible scientists, with these contributions being acknowledged through citations.

Ideally a committed code should conform to the rules required by Joss. Recognition should be extended to a broader range of scientists who have played a role in the development of the modeling system, even if their contributions have not been formally documented in publications. An inventory of these contributors will be upheld on the GEOframe website. When composing a paper, GEOframe users and developers should take into account the following guidelines:

- **CO-autorship**
  - Anticipated, if your published research has been enriched by a novel advancement, in other words, if this advancement has significantly shaped your study and is consequently elaborated upon in your paper;
  - To expedite the prompt publication of novel elements such as new components or algorithms, when a paper is inherently dependent on a code that features an unpublished, innovative algorithm, it is advisable to contemplate the incorporation of the author's algorithm (Sec. S4.1.3);
  - Is anticipated in cases where your research necessitated significant direct involvement from a developer, such as making substantial code modifications or assisting in experiment design, among other instances;
  - It's worth contemplating the inclusion of a broader range of scientists who have contributed to the modeling system, even if their contributions might not be formally documented in publications. A compilation of these researchers will be upheld on the GEOframe webpage.
- **Acknowledgements**: Deserving of contemplation are scientists who have engaged in established GEOframe code developments;
- **Citation of published paper**: Is anticipated when there exists a citable paper detailing a specific development. A descriptive account of the model along with a compilation of papers elucidating these advancements will be upheld on the GEOframe website.

S4.1.3 Recognition of new contributors

To facilitate the acknowledgment of noteworthy contributions warranting co-authorship consideration, we establish the following guidelines. Components lacking tags should be regarded as non-usable, unstable, unsafe, or new. Tagged components are the only ones to be freely employed, unless their tag number concludes with "**9**"; in such instances, the possibility of co-authorship must be deliberated. Other tag numbers permit unrestricted use of the component. For instance, version 1.0 is freely usable, whereas version 0.09 mandates a co-authorship discussion, despite its seemingly cautionary low number. These limitations remain in effect for a maximum of 1 year. Consequently, a version like 15.0009 could be utilized without restrictions following a one-year embargo in any scenario.

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