

**Response to reviewers**  
Geoscientific Model Development

*ForEdgeClim* v1.0: a 3D process-based microclimate model incorporating vertical and lateral radiative and thermal fluxes to simulate forest edge-to-core transitions

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## Letter to the Editor

Dear Editor,

We would like to thank you for handling our manuscript. We are also grateful to the reviewers for their thorough, constructive, and insightful comments, which have helped us to substantially improve the manuscript. We particularly appreciate that all reviewers recognised the novelty and relevance of the proposed modelling framework, highlighting its potential contribution to advancing process-based microclimate modelling within the community.

In response to the reviews, we have carefully revised the manuscript to improve the clarity and physical consistency of the model description, better position the scope of the current model version, and more explicitly distinguish between processes currently represented and those yet to be implemented in future work. In particular, we have clarified the physical interpretation of key model components, added explicit unit definitions, expanded the discussion of assumptions and limitations, and provided a more concrete and technically detailed roadmap for future model development.

Several reviewer suggestions involved substantial extensions of the model (e.g., explicit representation of wind-driven transport, detailed canopy structural separation, or fully coupled soil–plant–atmosphere processes). While we fully recognise the importance of these processes, their implementation would require significant additional model development and introduce considerable computational and technical complexity beyond the intended scope of this first model version. Instead, we have focused on strengthening the conceptual clarity of the framework and explicitly outlining how such processes can be incorporated in future developments. Importantly, this first model version is designed as a flexible foundation upon which such processes can be implemented, with the choice of extensions depending on the intended application and user-specific objectives.

At the same time, we have implemented several targeted improvements in the revised manuscript. These include the introduction of seasonally varying optical properties (leaf-on and leaf-off conditions) and the addition of new analyses to better contextualise model performance. In particular, we analysed model residuals as a function of wind speed and distance to the forest edge, conducted an uncertainty analysis of the surface temperature output, assessed the convergence of the Sobol sensitivity analysis (200 vs 400 samples), and evaluated the model's ability to resolve spatial temperature gradients. These analyses provide new insights into the drivers of model error and robustness of the sensitivity results, thereby strengthening the interpretation of model performance and informing priorities for future model development.

Overall, we believe that these revisions have improved the physical clarity of the model description and strengthened the discussion of its assumptions, limitations, and potential future extensions. We hope that the revised manuscript is now suitable for publication in *Geoscientific Model Development*.

Sincerely,  
The authors

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# 1 Reviewer 1: Ilya Maclean

## 1.1 General comments

### Reviewer 1 Comment 1

There is undoubtedly a strong and growing need for robust microclimate modelling approaches, particularly in forested systems where fine-scale thermal heterogeneity can strongly influence ecological processes. The manuscript addresses an important problem, and the attempt to develop a tractable, process-based framework is welcome.

However, the current presentation would benefit from greater physical clarity, closer engagement with the extensive microclimate modelling literature, and more precise definition of terms and units. Throughout the manuscript, model equations are presented without consistently specifying the units of each term. For a physically based model, dimensional consistency is important, and equations would benefit from explicit unit definitions (e.g.  $\text{W m}^{-2}$ ,  $\text{m s}^{-1}$ ,  $\text{J m}^{-3} \text{K}^{-1}$ , etc.) to avoid ambiguity and ensure reproducibility.

### Response:

We thank the reviewer for this overall assessment of the manuscript and for the constructive suggestions provided throughout the review.

We acknowledge that the current version of *ForEdgeClim* relies on several simplifying assumptions. The goal of this first model version is to provide a computationally efficient framework for simulating spatial microclimate temperature gradients within three-dimensional forest structures derived from TLS data. While we agree that a more comprehensive representation of canopy microclimate processes would further strengthen the model, many of the suggested extensions involve substantial additional model complexity and computational cost, and are therefore beyond the intended scope of this initial version.

In response to the reviewer's comments, we have improved the clarity and physical consistency of the model formulation. Units are now explicitly defined for all variables, constants, and parameters at their first occurrence. We have further clarified the representation of vegetation density and heat exchange processes, strengthened the linkage to the microclimate modelling literature, and expanded the discussion of model limitations and potential future developments.

All these improvements are outlined in more detail below, within the specific comments. Only for the more precise unit definitions an example is provided here; similar revisions have been applied consistently to all variables and equations throughout the manuscript.

Section 2.1.2 Air temperature, Lines 148–155:

### 2.1.2 Air temperature

Air temperature is estimated through a linear interpolation approach similar to that used in the microclimate models *microclimc* (Maclean and Klinges, 2021) and its successor *microclimf* (Maclean, 2025), which simulate only vertical energy and radiation fluxes.

In contrast, *ForEdgeClim* also resolves lateral fluxes:

$$T_{\text{air}} = \frac{(w_{\text{mX}} + w_{\text{mZ}}) g_{\text{m}} T_{\text{m}} + w_{\text{s}} g_{\text{s}} T_{\text{s}} + w_{\text{f}} g_{\text{f}} T_{\text{f}}}{(w_{\text{mX}} + w_{\text{mZ}}) g_{\text{m}} + w_{\text{s}} g_{\text{s}} + w_{\text{f}} g_{\text{f}}}, \quad (2)$$

where  $w$  represents a dimensionless weighting factor,  $g$  a convection coefficient ( $\text{W m}^{-2} \text{K}^{-1}$ ), and  $T$  temperature (K). Subscripts m, s, and f refer to the macroenvironment, soil surface, and forest surface, respectively, while subscripts mX and mZ denote the lateral (x-axis) and vertical (z-axis) macroenvironmental boundaries.

## 1.2 Specific comments

### Reviewer 1 Comment 2

Lines 100–109 – Iterative solution of the energy balance:

It is not made clear why the surface energy balance must be solved iteratively. In many comparable contexts, the system can be solved more efficiently using a Penman–Monteith formulation or related bulk-transfer approaches. The authors should clarify why iteration is necessary here, and whether a more computationally efficient analytical solution is possible.

### Response:

The surface energy balance in *ForEdgeClim* is solved iteratively because surface temperature appears in several non-linear terms of the energy balance, including longwave radiation emission (Stefan–Boltzmann law), sensible heat exchange, and latent heat flux. These terms depend explicitly on the unknown surface temperature, making an analytical solution impractical within the voxel-based framework of the model.

Unlike bulk canopy approaches such as the Penman–Monteith formulation, which represent the canopy as a spatially aggregated surface, *ForEdgeClim* resolves energy exchange at the scale of individual voxels within a three-dimensional forest structure derived from TLS data. In this spatially explicit representation, the energy balance must be solved separately for many surfaces with locally varying radiative and thermal conditions. For this reason, we adopt an iterative numerical approach to ensure convergence of the local surface temperature.

We clarified this explanation in the manuscript by explicitly stating why an iterative solution is required in the voxel-based framework and how it differs from bulk canopy formulations such as Penman–Monteith.

Section 2 Model description, Lines 105–113:

Each component of the energy budget depends explicitly on the local forest surface temperature (K), defined here as an effective surface temperature representing leaf and woody elements, weighted by their local structural density, through non-linear physical relationships. These include longwave radiation emission (Stefan–Boltzmann law), sensible heat exchange, and latent heat flux, all of which depend on the unknown surface temperature. As a result, the energy balance cannot be solved analytically within the voxel-based framework and is instead solved iteratively until convergence to a steady-state solution is achieved for a single moment in time.

Unlike bulk canopy approaches such as the Penman–Monteith formulation (Monteith, 1965), which represent the canopy as a spatially aggregated surface, *ForEdgeClim* resolves energy exchange at the scale of individual voxels within a three-dimensional forest structure derived from TLS data. In this spatially explicit representation, the energy balance must be solved separately for many surfaces with locally varying radiative and thermal conditions.

### Reviewer 1 Comment 3

Section 2.1.2 – Below-canopy air temperature:

The physical treatment of below-canopy air temperature is fairly questionable. It is now well established that Lagrangian approaches to fluid mechanics are required to rigorously describe scalar transport within and below plant canopies (see the seminal work of Raupach and subsequent developments). Air temperature at a given point below the canopy is not determined solely by local leaf temperature or local energy exchange. Rather, it reflects the cumulative influence of upstream canopy elements through advection and turbulent mixing. In other words, the temperature field represents an integrated effect of heat exchange along air parcel trajectories as they move through and downwind of the canopy. The current formulation appears to treat temperature as a locally determined variable, which risks neglecting this trajectory-dependent behaviour. The authors need to explain why a local formulation is sufficient in this context. In addition, foliage density does not appear to influence the formulation. If fluxes are expressed in standard units (e.g.  $\text{W m}^{-2}$ ), canopy leaf area density or LAI should explicitly affect the magnitude of exchange. As written, it is unclear how foliage density affects the flux exchange between the canopy and the air.

### Response:

We fully agree that the temperature field within and below plant canopies is strongly influenced by turbulent mixing and advection, and that Lagrangian approaches provide a rigorous framework for describing the trajectories of air parcels moving through heterogeneous canopy structures (Raupach, 1987, 1989). However, explicitly resolving such processes would require detailed modelling of canopy airflow and turbulence, typically through computational fluid dynamics (CFD) or large-eddy simulations (LES), which operate at spatial and temporal scales and computational costs far beyond the intended scope of *ForEdgeClim*.

Instead, *ForEdgeClim* adopts an Eulerian grid-based representation of the canopy environment, where air temperature is treated as a state variable defined for each voxel in the three-dimensional grid. Heat exchange between neighbouring voxels is parameterised through diffusive heat exchange and surface–air fluxes, which represent the net effect of turbulent mixing and small-scale air movement within the canopy. Similar Eulerian formulations are commonly used in land surface models and canopy energy balance models (Bonan, 2019; Campbell and Norman, 2000), where turbulent processes are represented through parameterised exchange coefficients rather than explicitly resolved flow dynamics.

In addition, *ForEdgeClim* solves for a steady-state temperature field rather than explicitly simulating the time-dependent evolution of air parcels moving through the canopy. As a result, the model does not attempt to resolve trajectory-dependent scalar transport. Instead, the cumulative effect of turbulent mixing and advection is represented implicitly through parameterised exchange

processes between neighbouring voxels and through boundary conditions imposed by the external macroclimate.

The goal of *ForEdgeClim* is not to resolve the detailed trajectories of air parcels within the canopy, but to capture the dominant radiative and thermal mechanisms that generate spatial temperature gradients along forest edge-to-core transitions. While this approach simplifies the underlying fluid dynamics, it allows the model to simulate microclimate patterns within complex three-dimensional forest structures derived from TLS data at relatively low computational cost.

We also agree that vegetation density plays a key role in controlling energy exchange between forest surfaces and the surrounding air. In *ForEdgeClim*, canopy structure is represented through the voxel density variable ( $\rho$ , dimensionless), which is derived from terrestrial laser scanning (TLS) data and scaled using plot-level plant area index (PAI). This density parameter represents the relative amount of vegetation material within each voxel and therefore acts as a proxy for local canopy surface availability.

Energy fluxes between the forest structure and the surrounding air are scaled by this voxel density. In practice, voxels with higher structural density represent a greater surface area of leaves and woody elements available for energy exchange, while voxels with low density represent more open air space and therefore weaker surface–air coupling. As a result, vegetation density directly influences the magnitude of sensible and latent heat exchange within the model.

We agree that both the implicit representation of turbulent transport and the role of vegetation density in scaling surface–air exchange were not explicitly stated in the original manuscript. We have therefore clarified these aspects in Section 2.1.2.

#### Section 2.1.2 Air temperature, Lines 156–173:

In this formulation, air temperature is treated as a state variable defined on an Eulerian grid, with each voxel representing a fixed position in space. Heat exchange between neighbouring voxels and between air and surrounding surfaces is parameterised through effective exchange processes, which represent the net effect of turbulent mixing and small-scale air movement within the canopy. This approach is consistent with commonly used formulations in microclimate and canopy energy balance models (Bonan, 2019; Campbell and Norman, 2000), where turbulent transport is not explicitly resolved but represented through bulk exchange coefficients.

In this context, linearisation refers to approximating a non-linear relationship – typically between net energy balance and air temperature – by a local linear function. This allows the model to update air temperature using a simplified linear equation rather than repeatedly solving a full non-linear energy balance formulation, as is done for the forest surface temperature, making it computationally more efficient while still retaining high accuracy. Such linearised closures are commonly assumed to be appropriate when air–surface temperature differences remain small relative to the absolute temperature, such that higher-order non-linear terms can be neglected (Stull, 2009; Monteith and Unsworth, 2013). These conditions are generally associated with sufficient air mixing, moderate radiation and humidity levels, and relatively homogeneous forest structures, under which turbulent transport can be reasonably approximated through bulk exchange processes.

In addition, vegetation density ( $\rho$ , dimensionless) directly scales the magnitude of surface–air energy exchange. In the model,  $\rho$  represents the effective fraction of vegetated surface within a voxel and enters explicitly in the formulations of sensible and latent heat fluxes (Eqs. (15) and (16)). Voxels with higher density therefore exhibit stronger coupling between surface and air temperatures, whereas low-density voxels represent more open air space with reduced exchange.

#### Reviewer 1 Comment 4

Sections 2.1.3 and 2.2.3 – Soil surface temperature and ground heat flux:

The soil surface temperature equation appears dimensionally inconsistent. If fluxes are expressed in  $\text{W m}^{-2}$ , there should be no need to introduce an explicit cross-sectional area term. Greater clarity on units is needed here. The assumption that temperature at 8 cm depth can be treated as fixed is problematic. At this depth, temperatures exhibit clear diurnal and seasonal variability. One typically needs to approach depths of  $\sim 2$  m before assuming quasi-constant temperature. Without a multi-layer soil heat transfer model, soil surface temperature cannot be derived mechanistically. As written, the approach appears to depend on continuous measurement at 8 cm depth, which limits transferability. Thermal conductivity ( $k$ ) is also treated as constant, yet it varies strongly with soil moisture content. I missed discussion of this issue.

#### Response:

First, we agree that the dimensional consistency of the soil heat flux equation was not correctly formulated in the original manuscript and indeed should not include a cross-sectional area term. Importantly, this inconsistency was limited to the manuscript, as the model code itself was implemented correctly without the cross-sectional area term. The formulation represents conductive heat transfer between the soil surface and a shallow subsurface reference layer. We have revised the equation description and clarified the units of all terms to ensure dimensional consistency throughout the energy balance formulation.

Second, we agree that soil temperature at 8 cm depth is not constant and exhibits both diurnal and seasonal variability. In the current version of *ForEdgeClim*, the temperature measured at 8 cm depth is used as a pragmatic reference temperature representing the shallow soil heat reservoir. While this reference temperature varies over time (following the observed soil temperature dynamics), it is treated as a prescribed boundary condition rather than being dynamically simulated within the model. This approach avoids the need for a multi-layer soil heat transfer model, which would substantially increase model complexity and computational cost. The aim of this formulation is therefore not to reproduce the full dynamics of soil heat diffusion, but to provide a first-order approximation of ground heat exchange within the local surface energy balance. Such simplified representations using shallow reference depths are commonly applied in surface energy balance approaches when subsurface processes are not resolved explicitly (Campbell and Norman, 2000).

We have clarified this modelling assumption in Section 2.1.3 and expanded the discussion of its limitations in Section 6.5. In particular, we now explicitly note that soil thermal conductivity and subsurface temperature dynamics depend on soil moisture and deeper soil processes, which are not currently represented in *ForEdgeClim*. In addition, a new figure has been included in Section

6.5 to illustrate and clarify the future development roadmap. An update to Section 2.2.3 can be found in the answer to your next comment (comment 5).

Section 2.1.3 Soil surface temperature, Lines 193–205:

### 2.1.3 Soil surface temperature

The soil surface temperature is modelled using the one-dimensional heat conduction equation (i.e., Fourier’s law):

$$T_s = T_{\text{soil}} + \frac{G z}{k_s}. \quad (1)$$

Here,  $T_{\text{soil}}$  (K) is the observed soil temperature at a reference depth. In our setup (see Sect. 3), this is measured at a depth of 8 cm at 20 locations within the forest transect. The variable  $z$  (m) represents the measurement depth (8 cm),  $G$  is the ground heat flux ( $\text{W m}^{-2}$ ), and  $k_s$  is the thermal conductivity of the soil ( $\text{W m}^{-1} \text{K}^{-1}$ ). The formulation represents conductive heat transfer between the soil surface and a shallow subsurface reference layer. This type of formulation is commonly used as a first-order approximation of ground heat exchange in models that do not explicitly resolve vertical soil heat transport (Campbell and Norman, 2000). The reference temperature  $T_{\text{soil}}$  varies over time following the measured soil temperature dynamics and is prescribed as a boundary condition. In the current implementation,  $k_s$  is treated as a constant parameter. In reality, soil thermal conductivity depends strongly on soil moisture content and soil composition, which are not explicitly represented in the model. As a result, spatial and temporal variability in soil thermal properties is not captured. The computation of  $G$  is described in Sect. 2.2.3.

Section 6.5 Model limitations and future development roadmap, Lines 898–904 and lines 937–941:

### Key limitations

[...]

Third, the representation of subsurface and ecohydrological processes is limited. Soil heat exchange is represented using a simplified conductive formulation with a shallow reference layer, and the model assumes quasi-steady-state conditions for each simulated time step. As a result, temporal heat storage and the characteristic phase lag between surface forcing and subsurface heat flux are not explicitly resolved (Campbell and Norman, 2000). In addition, water transport processes and plant hydraulics are not currently represented. Feedbacks between soil moisture, plant water status, and energy exchange – such as stomatal regulation of transpiration – are therefore not captured, which may influence microclimate dynamics under water-limited conditions.

[...]

### Future development roadmap

These limitations define a clear roadmap for future model development (Fig. 10).

[...]

A third priority is the integration of soil and plant water dynamics. Implementing a multi-layer soil heat and water balance scheme would explicitly represent vertical

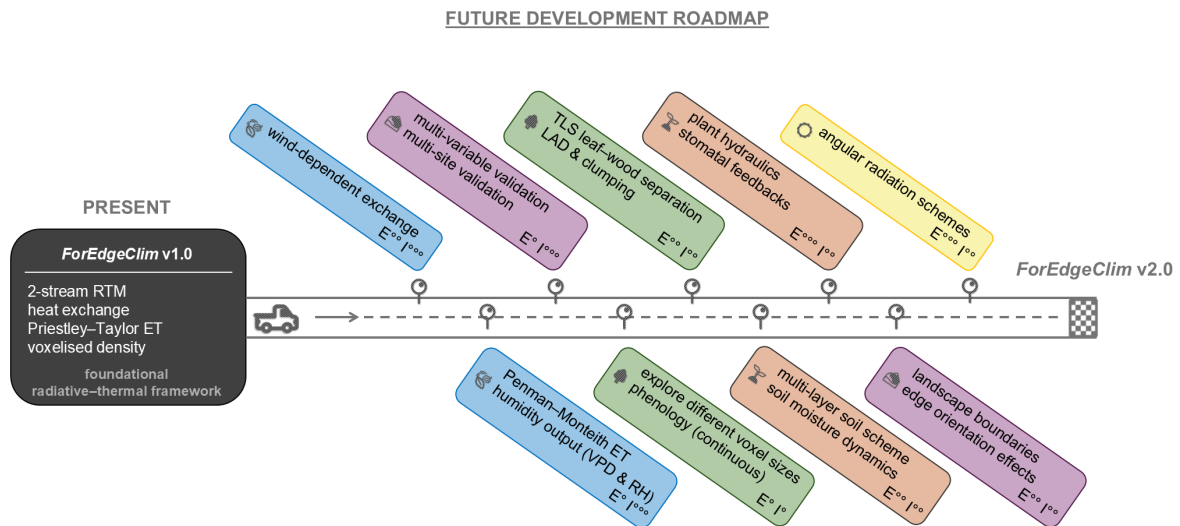


Figure 10: Conceptual development roadmap for the *ForEdgeClim* radiative-thermal core, illustrating the progression from the current model formulation (present) towards a target fully coupled three-dimensional microclimate model. The road visualisation represents a continuous development trajectory along which key model extensions are introduced, including atmospheric coupling (blue), improved boundary conditions and validation (purple), canopy structure refinement (green), soil-plant interactions (brown), and advanced radiation schemes (yellow). For each extension, the expected implementation effort (E) and potential model impact (I) are indicated using a qualitative rating, where the number of symbols (°) reflects relative magnitude (e.g.,  $E^\circ$  denotes low effort,  $I^{\circ\circ\circ}$  denotes high impact).

heat diffusion and soil moisture dynamics, building on the current vertical heat exchange formulation within the voxel grid. Coupling this with a plant hydraulic framework would enable feedback between soil moisture, plant water status, and stomatal conductance, thereby improving the representation of evapotranspiration and energy partitioning under varying environmental conditions.

#### Reviewer 1 Comment 5

In Section 2.2.3, the ground heat flux method will not reproduce the well-established quarter-cycle phase shift (diurnal or seasonal) between surface radiation forcing and subsurface heat flux. Instead, fluxes appear to mirror radiation directly, meaning the heat storage effect is not properly represented. It would be worth exploring the de Vries / Van Wijk method as described in Campbell & Norman, which provides a more physically consistent treatment of soil heat storage consistent with the framework presented in this paper.

#### Response:

We agree that in soils, heat diffusion leads to a characteristic phase shift between surface forcing and subsurface heat flux, typically approximating a quarter-cycle lag for diurnal or seasonal temperature variations (Campbell and Norman, 2000). This behaviour emerges from time-dependent heat diffusion within the soil profile.

In the current version of *ForEdgeClim*, the soil heat flux formulation is intentionally simplified and represents conductive heat exchange between the soil surface and a shallow subsurface reference temperature. The model is solved for individual time steps assuming equilibrium conditions rather than explicitly simulating the temporal evolution of soil temperature profiles.

As a consequence, the model does not reproduce the phase lag associated with dynamic soil heat storage. However, resolving such phase lags requires a time-dependent representation of soil heat diffusion, which is beyond the scope of the present model and not required for the intended application focusing on instantaneous energy balance conditions.

The purpose of the current formulation is to provide a first-order representation of ground heat exchange within the local surface energy balance while maintaining computational efficiency within the voxel-based 3D framework. We agree that a more physically detailed treatment of soil heat storage, such as the approach described by de Vries and Van Wijk (as presented in Campbell and Norman (2000)), would improve the representation of subsurface thermal dynamics.

We have therefore clarified in Section 2.2.3 that the current ground heat flux formulation represents a simplified conductive exchange rather than a time-resolved soil heat diffusion model. We have expanded the discussion in Section 6.5 to acknowledge this limitation and to highlight the implementation of a multi-layer soil heat diffusion scheme as a potential direction for future model development, which is beyond the scope of the current study and not required for the primary modelling objectives of this first model version. We refer to our response to the previous comment (comment 4) for the expansion of Section 6.5.

Section 2.2.3 Ground heat flux, Lines 258–269:

### 2.2.3 Ground heat flux

Ground heat flux ( $G$ ) represents the transfer of energy between the ground surface and the underlying soil. It is modelled as a fixed proportion of the net radiation at the ground surface:

$$G = p (1 - \rho) R_n , \quad (12)$$

following the approach implemented in the *SCOPE 2.0* model (Yang et al., 2021). Here,  $p$  is the fraction of  $R_n$  that is absorbed by the soil surface and  $\rho$  is the forest structural density of the voxel layer directly above the soil (dimensionless). Ground heat flux is therefore reduced under dense vegetation cover, where less radiation reaches the soil surface.

Eq. (12) provides a simplified local closure of the surface energy balance and implicitly assumes that ground heat flux responds instantaneously to net radiation. As such, it does not explicitly represent heat storage or diffusion within the soil profile.

The resulting flux is used to estimate soil surface temperature (Sect. 2.1.3), which in turn influences near-surface air temperature (Sect. 2.1.2) and the overall energy balance.

**Reviewer 1 Comment 6**

Section 2.2.4 – Sensible heat flux:

The terminology becomes imprecise with respect to thermal energy transfer from forest surfaces to the surrounding air. You introduce a forest–air convection coefficient,  $g$ , but in conventional notation  $g$  typically denotes leaf boundary layer conductance. The discussion also refers to molecular diffusion, whereas in forest environments free and forced laminar convection dominate at the leaf surface, and turbulent heat transfer is often critical within the air. Given the method used to compute air temperature, turbulent exchange likely needs to be explicitly accounted for separate to leaf boundary layer conductance. The authors should clearly define the physical meaning of  $g$ , specify its units, and describe how it is parameterised and scaled.

**Response:**

We agree that the terminology used in the original manuscript could be more clear. In the current formulation of *ForEdgeClim*, the parameter  $g_f$  ( $\text{W m}^{-2} \text{K}^{-1}$ ) represents a bulk forest–air heat exchange coefficient that parameterises the net transfer of sensible heat between forest surfaces (leaves, branches, and trunks) and the surrounding air. The parameter therefore represents the combined effects of several physical processes, including leaf boundary layer convection, small-scale air movement within the canopy, and turbulent mixing in the surrounding air.

We agree that the wording referring to "molecular diffusion" was imprecise. The dominant mechanisms for heat exchange between vegetation surfaces and the surrounding air are free and forced convection at the surface boundary layer and turbulent transport within the canopy airspace. In the model, these processes are not resolved explicitly but are represented implicitly through the bulk heat exchange coefficient  $g_f$ .

To avoid confusion with the conventional notation for conductances (typically expressed in units of  $\text{m s}^{-1}$ ), we have clarified that  $g_f$  represents a bulk sensible heat transfer coefficient with units of  $\text{W m}^{-2} \text{K}^{-1}$ .

We also acknowledge that in real forest environments, sensible heat exchange between surfaces and the atmosphere depends strongly on wind-driven turbulence and canopy aerodynamic characteristics. In the current model version,  $g_f$  is treated as a calibrated parameter that represents the effective heat exchange under typical canopy conditions. In future model developments, we aim to extend this formulation by linking the heat exchange coefficient to wind speed and canopy structure, allowing  $g_f$  to vary dynamically as a function of atmospheric conditions and aerodynamic conductance. This extension would allow a more mechanistic representation of wind-driven turbulent heat exchange within the *ForEdgeClim* framework.

We revised Section 2.2.4 to clarify the physical meaning of the forest–air heat exchange coefficient  $g_f$ , specify its units ( $\text{W m}^{-2} \text{K}^{-1}$ ), and replace the reference to molecular diffusion with a more accurate description of convective and turbulent heat transfer processes. In addition, Section 6.5 was expanded to note that future model developments may link the sensible heat exchange coefficient  $g_f$  to wind speed and canopy aerodynamic properties, allowing a dynamic representation of wind-driven turbulent heat exchange.

Section 2.2.4 Sensible heat flux, Lines 270–295:

#### 2.2.4 Sensible heat flux

Sensible heat flux ( $H$ ) represents the transfer of thermal energy between forest surfaces and the surrounding air. In *ForEdgeClim*, this process is simulated in three dimensions and includes two components: (i) heat exchange between adjacent air voxels:

$$D = h A \frac{\Delta T_{\text{air}}}{\Delta x}, \quad (13)$$

$$T_{\text{air,new}} = T_{\text{air,old}} - \frac{D}{c_p \rho_{\text{air}} V}, \quad (14)$$

and (ii) heat exchange between forest elements and the air:

$$H = \rho g_f (T_f - T_{\text{air}}), \quad (15)$$

where  $h$  ( $\text{W m}^{-1} \text{K}^{-1}$ ) is an effective heat transfer coefficient governing air–air exchange between adjacent voxels, and  $g_f$  ( $\text{W m}^{-2} \text{K}^{-1}$ ) is a bulk forest–air sensible heat transfer coefficient.

Boundary conditions allow heat exchange with the macroenvironment at the canopy and forest edge, with the soil at the lower boundary, and impose a no-flux condition at the forest core.

In Eqs. (13)–(15),  $A$  is the surface area of one voxel face ( $\text{m}^2$ ),  $\Delta T_{\text{air}}$  is the air temperature difference between adjacent voxels (K),  $\Delta x$  is the voxel size (m),  $T_{\text{air,new}}$  and  $T_{\text{air,old}}$  are the updated and previous air temperatures (K),  $c_p$  ( $\text{J kg}^{-1} \text{K}^{-1}$ ) is the specific heat capacity of air,  $\rho_{\text{air}}$  ( $\text{kg m}^{-3}$ ) is air density,  $V$  is the voxel volume ( $\text{m}^3$ ), and  $\rho$  is the voxel’s forest structural normalised density (dimensionless).

The air–air heat exchange term (Eqs. (13) and (14)) represents effective thermal transport driven by local temperature gradients. This parameterisation does not explicitly resolve the underlying transport processes, but instead captures their combined effect at the voxel scale through the coefficient  $h$ . In practice, heat transport is expected to be dominated by turbulent mixing under most conditions, while molecular diffusion contributes only marginally.

The forest–air heat exchange term (Eq. (15)) represents the net sensible heat transfer between vegetation surfaces (e.g., leaves, branches, and stems) and the surrounding air. The coefficient  $g_f$  is a bulk heat transfer parameter that implicitly accounts for boundary layer convection at vegetation surfaces as well as small-scale air movement and turbulent mixing within the canopy. It is treated here as an effective parameter representing typical canopy conditions.

This formulation allows sensible heat fluxes to respond to local temperature gradients and forest structural density, while maintaining computational efficiency within the voxel-based framework.

Section 6.5 Model limitations and future development roadmap, Lines 877–886 and lines 915–924:

#### Key limitations

Several limitations arise from the simplified representation of physical processes in the current model version.

First, canopy–atmosphere exchange processes are only partially represented. Wind-driven turbulence, advection, and momentum transfer are not explicitly simulated, although these processes play a key role in shaping forest microclimates, particularly at forest edges (Chen et al., 1995; De Frenne et al., 2021). Sensible heat exchange is parameterised using a bulk heat transfer coefficient, and evapotranspiration is represented using a Priestley–Taylor formulation, which assumes radiation-driven latent heat fluxes and neglects explicit aerodynamic control. While this assumption is often reasonable for forest interior conditions, it may be less appropriate near forest edges where horizontal advection of heat and moisture can modify evaporative demand. This limitation is also reflected in the residual analysis, which indicates that model–observation discrepancies increase under higher wind speeds, particularly in structurally open areas where atmospheric coupling is enhanced.

[ . . . ]

### Future development roadmap

These limitations define a clear roadmap for future model development (Fig. 10).

A first priority is to improve the representation of canopy–atmosphere exchange by incorporating wind-dependent aerodynamic processes. This can be achieved within the existing voxel-based framework by linking the current bulk heat transfer coefficients ( $g_m$ ,  $g_s$ ,  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ ,  $i_f$ ) to wind speed and canopy structural properties (Maurer et al., 2013; Kimura et al., 2020; Flayyih Al-Rikabi et al., 2024). Such an extension would allow turbulent mixing and advective heat transport to be represented more explicitly, while retaining the current parameterisation structure. Extending the evapotranspiration formulation to a Penman–Monteith framework would further enable explicit representation of canopy resistance and atmospheric demand, and facilitate the inclusion of humidity-related state variables such as vapour pressure deficit and relative humidity.

#### Reviewer 1 Comment 7

Section 2.2.5 – Latent heat flux:

This section is also problematic. The discussion focuses on evaporation, but in forest systems transpiration typically represents a substantial component of latent heat flux. Transpiration is controlled by stomatal conductance, which does not appear to be included in the formulation. The manuscript argues that evaporation is primarily driven by available radiative energy and surface humidity. However, radiative energy drives evapotranspiration both through direct surface energy availability and via its effects on PAR and stomatal conductance. Only the most direct pathway appears to be represented. Ignoring stomatal control risks substantial overestimation of latent heat flux, particularly under conditions where stomata are partially closed.

#### Response:

We agree that in forest ecosystems, transpiration through stomatal conductance often represents a substantial component of evapotranspiration. In the current version of *ForEdgeClim*, latent heat flux is estimated using the Priestley–Taylor formulation, which represents a bulk canopy approximation of evapotranspiration primarily driven by available radiative energy.

In this formulation, stomatal regulation is not represented explicitly. Instead, the empirical Priestley–Taylor coefficient ( $\alpha$ , dimensionless) provides a bulk correction that reflects the average effects of canopy resistance, atmospheric conditions, and vegetation controls on evapotranspiration (Lhomme, 1997). However, we acknowledge that this approach cannot represent the dynamic response of stomata to changing environmental conditions such as vapour pressure deficit (VPD), soil moisture, or light availability.

We further note that, within the scope of the current study, the impact of this simplification on the primary model output (air temperature) appears limited. The sensitivity analysis indicates that parameters controlling latent heat flux contribute on average 9.3 % and 8.4 % to the variance in simulated horizontal and vertical air temperature, respectively. This confirms that latent heat flux represents a secondary control compared to other parameters governing heat exchange (e.g., bulk convection coefficients and distances of influence), suggesting that potential biases in evapotranspiration are unlikely to strongly affect the simulated temperature gradients.

The aim of the current model version is to capture the dominant radiative and thermal drivers of microclimate temperature gradients within a computationally efficient voxel-based framework. In future versions of *ForEdgeClim*, we aim to extend the latent heat flux formulation by implementing a Penman–Monteith-based approach. Such a formulation would allow explicit representation of aerodynamic conductance, canopy resistance, and the influence of VPD on evapotranspiration, thereby providing a more mechanistic representation of stomatal regulation and plant physiological control on transpiration while remaining compatible with the voxel-based energy balance framework.

Section 2.2.5 was revised to clarify that latent heat flux is estimated using the Priestley–Taylor formulation as a bulk evapotranspiration approximation, where stomatal regulation is not represented explicitly but represented only as a bulk approximation through the empirical Priestley–Taylor coefficient. In addition, Section 6.5 was expanded to acknowledge the limitations of this approach and to outline the potential implementation of a Penman–Monteith-based formulation in future model versions to explicitly account for canopy resistance and VPD. For this expansion of Section 6.5, we refer to our answer on your previous comment (comment 6).

Section 2.2.5 Latent heat flux, Lines 296–313:

### 2.2.5 Latent heat flux

Latent heat flux ( $LE$ ) represents the transfer of energy associated with phase changes of water, including both evaporation and transpiration (i.e., evapotranspiration) from forest surfaces to the atmosphere. In *ForEdgeClim*,  $LE$  is estimated using the empirical Priestley–Taylor method:

$$LE = \rho \alpha R_n \frac{s(T_f)}{s(T_f) + \gamma}, \quad (16)$$

which provides a simplified form of the Penman–Monteith equation by representing evapotranspiration as a function of available radiative energy (?). Here,  $\alpha$  (dimensionless) is the Priestley–Taylor coefficient,  $\gamma$  is the psychrometric constant ( $\text{kPa K}^{-1}$ ), and  $s(T_f)$  is the slope of the saturation vapour pressure curve.

In this formulation, evapotranspiration is represented as a bulk canopy flux. Stomatal

regulation and canopy resistance are not explicitly resolved; instead, their combined effects, together with atmospheric controls, are implicitly captured in the empirical coefficient  $\alpha$ . As a result, this approach provides a first-order approximation of latent heat flux under conditions where evapotranspiration is primarily energy-limited (Monteith and Unsworth, 2013).

The slope of the saturation vapour pressure curve is defined as:

$$s(T_f) = 4098 \frac{e_s(T_f)}{(T_f - 35.85)^2} \cdot \quad (17)$$

The saturation vapour pressure  $e_s(T_f)$  is estimated using the empirical formulation of Tetens:

$$e_s(T_f) = 0.6108 \cdot \exp\left(\frac{17.27 (T_f - 273.15)}{T_f - 35.85}\right), \quad (18)$$

which provides a reliable approximation of the Clausius–Clapeyron relationship for temperatures up to 50 °C (Anyadike, 1984).

#### Reviewer 1 Comment 8

Model testing:

Some of the limitations outlined above would be more easily reconciled if the model demonstrated strong predictive performance. Figure 3 is interesting, but the discrepancies between modelled and measured values appear large relative to the effect sizes being examined. In several cases, the measured differences between forest interior and core are smaller than the deviations between modelled and observed values. This raises concerns about whether the model can reliably resolve the spatial contrasts it seeks to quantify.

#### Response:

The model's ability to resolve spatial temperature gradients depends not only on overall model–observation discrepancies but also on the magnitude of the observed edge-to-core differences. We acknowledge that, in some cases, the deviations between modelled and observed temperatures are comparable to or larger than the observed gradients themselves, which can limit the model's ability to resolve small spatial contrasts. We note that Fig. 3 represents a single 24-hour example and is therefore not fully representative of the model's overall performance.

To provide a more comprehensive assessment, we analysed modelled and observed edge-to-core temperature gradients across all simulated time steps (24 h  $\times$  30/31 days  $\times$  4 seasons). This analysis combines an evaluation of the agreement between modelled and observed gradients and a quantification of model error relative to the magnitude of the observed spatial gradients. The results of this analysis are now presented in the main text (Fig. 7).

The comparison shows that modelled gradients broadly follow the observed direction, but with substantial scatter and seasonal variability, indicating limitations in reproducing gradient magnitude across all conditions. Importantly, the complementary analysis demonstrates that model performance strongly depends on the magnitude of the observed gradients. For larger gradients, model errors are generally smaller than the magnitude of the gradients, indicating that the model is able to resolve pronounced spatial temperature contrasts. In contrast, when observed

gradients are small (e.g., below 1 °C), model errors are often of similar magnitude or larger than the gradients, which reduces the model's ability to reliably distinguish weak spatial differences.

This behaviour is expected, as edge-to-core temperature gradients approach zero under near-isothermal conditions, where even small absolute model errors can exceed the signal. As such, the apparent limitation in resolving weak gradients reflects a low signal-to-noise ratio rather than a systematic failure of the model to capture spatial patterns.

These patterns are consistent with the calibration strategy, which targets point-wise air temperature (RMSE) rather than explicitly constraining the edge-to-core temperature gradient, and highlight that small spatial contrasts are inherently more sensitive to model error.

To address the reviewer's concern, we have revised the text accompanying Fig. 3 to explicitly distinguish between periods of strong and weak spatial gradients, and added a dedicated analysis in the validation section that evaluates both the agreement in gradient magnitude and the ability of the model to resolve spatial temperature contrasts relative to their magnitude.

#### Section 5.1 Prognostic variables, Lines 545–563:

Air temperature dynamics differ clearly between the forest core, the forest edge, and the open area outside the forest (Fig. 3). Temperatures at the edge consistently rise faster during the day than those in the core, and their diurnal amplitude is markedly larger. This contrast is particularly well captured by the model during the morning hours, when edge–core temperature gradients are strongest. During this period, modelled gradients closely match observations, indicating that the model successfully resolves the edge-to-core temperature signal.

Observed temperatures at the forest edge and core converge in the afternoon, whereas the model maintains a stronger edge–core contrast. This indicates that, for this particular day, the model overestimates spatial temperature gradients when the observed system becomes more thermally homogeneous.

This pattern reflects stronger exposure to radiative and advective forcing at the forest edge, whereas conditions within the forest interior remain more buffered throughout the day.

In Fig. 3, observed temperatures at the forest edge show a more abrupt decline after solar noon than simulated temperatures, potentially reflecting the sudden loss of direct lateral sunlight when the sun angle shifts and the sensor becomes shaded by the canopy. This sharp transition is captured by the in situ measurements but is smoothed in the model, which represents radiative forcing and heat exchange at the voxel scale rather than resolving sensor-scale shading effects. The convergence of observed temperatures in the afternoon during this period may further reflect increased turbulent mixing within the forest, which is not explicitly accounted for in the model and may contribute to the persistence of stronger gradients in the simulations.

A comprehensive evaluation of modelled versus observed edge–core temperature gradients across all simulated time steps is presented in Sect. 5.3.2, combining an assessment of the agreement in gradient magnitude with an analysis of the model's ability to resolve spatial temperature contrasts relative to its uncertainty.

Section 5.3.2 Validation (part of Section 5 Results), Lines 696–713:

Across the full simulation period, modelled and observed edge–core temperature gradients show a moderate level of agreement, with modelled gradients broadly following the observed direction (Fig. 7a). However, substantial scatter and clear seasonal differences indicate that the model has limited ability to accurately reproduce the magnitude of these gradients across all conditions, even though the presence of spatial gradients is generally captured.

This variability in model performance can be explained by differences in the magnitude of the observed gradients. The proportion of cases in which model error is smaller than the observed gradient increases markedly with gradient magnitude (Fig. 7b). For larger gradients, the majority of cases fall below the threshold where model error exceeds the observed gradient, indicating that the model is generally able to resolve pronounced spatial temperature differences. In contrast, for small gradients (e.g., below approximately 1 °C), the proportion of cases where model error exceeds the signal is substantially higher, indicating limited ability to resolve weak spatial contrasts.

This pattern reflects the fact that edge–core temperature differences approach zero under near-isothermal conditions, where even small absolute model errors can exceed the signal. As a result, the model’s ability to resolve weak spatial gradients is inherently limited under these conditions due to a low signal-to-noise ratio, rather than a systematic misrepresentation of spatial patterns.

Overall, these results indicate that the model is capable of resolving spatial temperature gradients when they are sufficiently pronounced, but that caution is required when interpreting simulated gradients under conditions where observed differences are small. This behaviour is consistent with the calibration strategy, which targets point-wise air temperature (RMSE) rather than explicitly constraining the edge–core temperature gradient.

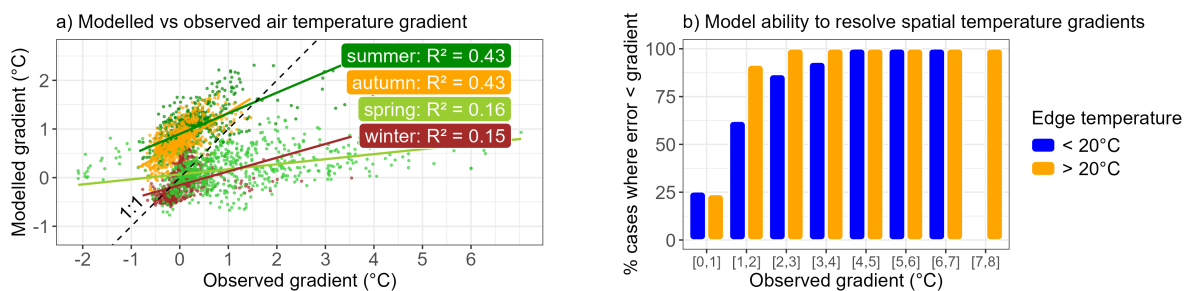


Figure 7: Comparison of modelled and observed edge–core air temperature gradients across all simulated time steps using a single annually calibrated parameter set. (a) Relationship between modelled and observed gradients, coloured by month (brown: winter, light green: spring, dark green: summer, orange: autumn). The dashed line indicates the 1:1 relationship. (b) Model performance as a function of observed gradient magnitude, expressed as the percentage of cases in which the absolute mean error (AME) between modelled and observed gradients is smaller than the observed gradient. Bars are aggregated across bins of observed gradient values, with blue and orange indicating cooler ( $\leq 20$  °C) and warmer ( $> 20$  °C) edge temperatures, respectively.

**Reviewer 1 Comment 9**

Overall assessment:

The model is not without merit and addresses an important problem and does seem to perform moderately well. However, it rests on several simplifying assumptions that limit its physical realism. Greater clarity on units, stronger engagement with existing microclimate modelling literature, and more rigorous treatment of canopy turbulence, soil heat storage, and stomatal control would substantially strengthen the manuscript.

**Response:**

Overall, we believe the revisions have improved the physical clarity of the model description and strengthened the discussion of its assumptions, limitations, and potential future extensions. Importantly, we emphasise that the novelty of *ForEdgeClim* lies in its explicit three-dimensional representation of forest structure, which enables the simulation of spatial microclimate gradients. While we agree that a more rigorous treatment of all underlying processes would ultimately improve model realism, a full physical description of these processes was beyond the scope of the present study.

## 2 Reviewer 2: Anonymous

### 2.1 General comments

#### Reviewer 2 Comment 1

*ForEdgeClim* addresses a genuine gap in the microclimate modelling landscape. The 3D voxel framework, the coupling with high-resolution TLS data, and the transparent sensitivity and calibration analyses represent real contributions. The authors deserve credit for tackling a difficult problem and for making their code and data openly available.

However, in its current form, the model is at a rather early stage. The radiative transfer component is reasonably developed, but the absence of wind-driven processes, the lack of leaf-wood separation despite having TLS data ideally suited for it, the highly simplified soil heat flux, the temperature-only output, and the evaluation at a single site all limit the model's physical realism and demonstrated generalisability. Several of the "semi-empirical" parameters ( $i_m$ ,  $i_s$ ,  $g_f$ ) are effectively doing the work of unresolved physical processes, and the future development discussion remains too vague to assess the model's trajectory.

I want to emphasise that none of these issues are fatal. *ForEdgeClim* v1.0 provides a working framework that can serve as a foundation for meaningful advances. But the manuscript, as currently written, does not sufficiently distinguish between what the model achieves now and what it aspires to achieve. A more honest framing of the current capabilities, combined with a concrete and technically specific development roadmap, would substantially strengthen the paper and provide much greater value to the community.

I encourage the authors to continue this important work. The problem they are tackling: fine-scale microclimate modelling in fragmented forests, is one of the key challenges in forest ecology and biodiversity science. With improvements, *ForEdgeClim* has the potential to become a genuinely useful tool for the community.

#### Response:

We thank the reviewer for the constructive and thoughtful assessment of our manuscript and for recognising the contribution of the *ForEdgeClim* framework to the microclimate modelling community. We appreciate the reviewer's positive evaluation of the voxel-based modelling approach, the integration of high-resolution TLS data, and the transparent sensitivity and calibration analyses.

We agree that the current model version represents an initial step towards a more comprehensive microclimate modelling framework. The primary objective of *ForEdgeClim* v1.0 is to introduce a computationally efficient 3D modelling framework capable of simulating temperature gradients along forest edge-to-core transitions using detailed structural information derived from TLS data. In this context, the deliberately simple model structure is intentional: the aim of this first version is to establish a flexible and transparent process-based foundation rather than to provide a fully comprehensive representation of all relevant micrometeorological processes.

Consistent with the reviewer's observation that the model can serve as a foundation for meaningful advances, we explicitly position *ForEdgeClim* v1.0 as a modular framework that can be further developed depending on the specific research questions and applications of interest. For example, the current structure allows future extensions to focus on particular processes such as wind-driven turbulent exchange, canopy physiological regulation, soil heat dynamics, or structural refinement (e.g., leaf-wood separation), depending on the needs of different users and study systems.

In response to the reviewer's comments, we have revised the manuscript to more clearly distinguish between the processes currently represented in the model and processes that are not yet included but represent important directions for future development. In particular, we have expanded the discussion of model limitations and future extensions, including the potential incorporation of wind-driven turbulent exchange, improved soil heat storage formulations, explicit representation of stomatal control and canopy resistance in evapotranspiration, and more detailed canopy structural representations.

We also agree that some model parameters currently act as effective representations of unresolved processes. We have highlighted those in the revised manuscript and expanded the discussion of how future model developments may replace such empirical parameters with more mechanistic formulations.

Overall, the revisions aim to provide a clearer description of the current capabilities of *ForEdge-Clim* v1.0 while outlining a more concrete development trajectory for future model versions. All the improvements are outlined in more detail below, within the specific comments.

## 2.2 Major comments

### Reviewer 2 Comment 2

Absence of wind and turbulent transport:

My most fundamental concern is that wind speed and turbulent transport are entirely absent from the model. There is no representation of advection, momentum transfer, or wind-driven mixing anywhere in *ForEdgeClim*. The sensible heat exchange (Eq. 15) relies on a static convection coefficient  $g_f$  that does not depend on wind speed, atmospheric stability, or any aerodynamic quantity. Air-to-air heat transfer between voxels is modelled as molecular conduction (Eqs. 13-14), which is orders of magnitude weaker than turbulent heat transport in real forest environments.

This omission is particularly consequential for a model that specifically targets forest edges. The reason edges are microclimatically distinct is the combined effect of lateral radiation penetration wind exposure. Warm or cold air is advected horizontally from adjacent open landscapes into the forest, and the penetration depth of this thermal signal is largely governed by canopy drag on the airflow. Without wind, the model must rely on the static "distance of influence" parameters ( $i_m$ ,  $i_s$ ) to prescribe how far the macroenvironmental signal propagates – but this penetration depth is physically set by wind-driven processes. The consistent convergence of  $i_m$  towards its upper bound (60 m) in calibration may be a symptom of the model stretching a static parameter to compensate for a missing dynamic process.

Furthermore, the Priestley–Taylor formulation for latent heat (Eq. 16) is justified as appropriate when advection is negligible – but at forest edges, advection is precisely not negligible.

Given the above, I feel the current model is more accurately described as a 3D radiative-thermal equilibrium model rather than a comprehensive microclimate model. The term "microclimate" in the biophysical literature carries the expectation of capturing the dominant atmospheric processes that shape local climate, and wind is unquestionably one of them.

I would suggest reframe the model's scope more precisely. The title or subtitle could be adjusted to reflect the radiative-thermal nature of the current framework (e.g., "...incorporating vertical and lateral radiative and thermal fluxes..."). Or at minimum, state clearly in the abstract and introduction, **not just in Section 6.5**, that wind processes are excluded. Discuss quantitatively when the no-wind assumption is expected to break down. The authors have 2 years of meteorological station data. Checking whether model residuals correlate with observed wind speed is a straightforward analysis that would either support the no-wind assumption or clearly delineate the model's domain of validity. Also provide a concrete technical plan for incorporating wind (see Major Comment 5 below) would be another way to improve.

### Response:

We fully agree that wind-driven turbulence, advection, and canopy–atmosphere momentum exchange play a fundamental role in shaping forest microclimates, particularly at forest edges where lateral exchange with the surrounding landscape can strongly influence temperature patterns. The current version of *ForEdgeClim* does not explicitly represent wind speed, aerodynamic conductance, or advective heat transport. Instead, the model focuses on radiative and thermal energy exchange processes within a three-dimensional voxel representation of forest structure.

The aim of *ForEdgeClim* v1.0 is therefore not to provide a fully coupled canopy micrometeorological model, but to introduce a computationally efficient 3D radiative–thermal framework capable

of resolving spatial microclimate gradients within structurally complex forest environments derived from TLS data. As the reviewer correctly notes, the absence of wind-driven processes implies that some model parameters (e.g., the distance-of-influence parameters  $i_m$ ,  $i_s$ , and  $i_f$ ) act as effective representations of processes that are not yet explicitly resolved. The present model therefore focuses on resolving the radiative and thermal drivers of spatial microclimate gradients, while recognising that wind-driven processes represent an important direction for future model development.

In response to the reviewer's suggestion, we have revised the manuscript to more clearly state the scope of the current model version. In particular, we now explicitly state in the abstract and introduction that the present model version focuses on radiative and thermal energy exchanges and does not explicitly represent wind-driven turbulent transport. In addition, we have adjusted the title of the manuscript to "*ForEdgeClim* v1.0: a 3D process-based microclimate model incorporating vertical and lateral radiative and thermal fluxes to simulate forest edge-to-core transitions" to better reflect the current scope of the model.

We agree that wind-driven advection is likely to play an important role in determining the penetration depth of macroclimatic signals into forest interiors. In future model developments, we aim to extend the current framework by incorporating wind-dependent aerodynamic exchange processes. For example, the current bulk convection coefficients ( $g_f$ ,  $g_s$ , and  $g_m$ ) and distances of influence ( $i_f$ ,  $i_s$ , and  $i_m$ ) could be linked to wind speed and canopy aerodynamic properties, allowing the model to represent wind-driven turbulent heat exchange within the voxel framework.

To directly assess the potential influence of wind-driven processes not represented in the current model formulation, we now include an additional analysis in the main manuscript in which model residuals are evaluated as a function of observed wind speed and distance to the forest edge. This analysis allows us to quantify how model performance varies under different wind conditions and along the edge-to-core gradient, and to identify conditions under which the omission of wind-driven processes is most consequential.

Overall, we have revised the manuscript to more clearly frame *ForEdgeClim* v1.0 as a radiative–thermal microclimate modelling framework and to provide a more concrete roadmap for incorporating wind-driven processes in future model versions. This framing clarifies the scope of the current model version while preserving flexibility for incorporating additional micrometeorological processes in future developments.

Title:

***ForEdgeClim* v1.0: a 3D process-based microclimate model incorporating vertical and lateral radiative and thermal fluxes to simulate forest edge-to-core transitions**

Abstract, Lines 10–13:

Building on this detailed structural representation, *ForEdgeClim* couples meteorological forcing with a physically based energy balance framework – including shortwave and longwave radiation, sensible and latent heat fluxes, and soil heat exchange – to resolve microclimate dynamics in three dimensions, while focussing on radiative and thermal energy exchanges and representing wind-driven processes implicitly.

Section 1 Introduction, Lines 67–69:

*ForEdgeClim* explicitly represents both vertical and horizontal energy fluxes, including radiative transfer and heat exchange, resolved within a 3D voxel-based grid, with a primary focus on radiative and thermal processes while wind-driven processes are represented implicitly.

Section 4.2.2 Validation (part of Section 4 Model evaluation), Lines 518–519:

To assess the potential influence of wind-driven processes not explicitly represented in the model, model residuals were analysed as a function of observed wind speed and distance to the forest edge.

Section 5.3.3 Influence of wind speed on model residuals (part of Section 5 Results), Lines 714–740:

### 5.3.3 Influence of wind speed on model residuals

In the current implementation of *ForEdgeClim*, wind-driven processes are not explicitly represented. To assess the potential influence of this omission, model residuals were analysed as a function of observed wind speed and distance to the forest edge (Fig. 8).

Overall, the influence of wind speed on model residuals, both during night- and daytime, appears limited, as indicated by the relatively small slopes across all spatial positions ( $1e^{-3}$ – $1e^{-1}$  °C m<sup>-1</sup> s in absolute order of magnitude). This suggests that wind-driven processes are not a dominant control on model performance under the conditions considered here. However, across all distances, residuals consistently increase with wind speed during both daytime and nighttime, indicating that wind-related processes are not yet fully captured by the current model formulation. The analysis spans four seasons, each represented by one month, suggesting that these patterns are robust across a range of environmental conditions.

Model performance nevertheless shows a clear but non-monotonic spatial pattern. Residuals are relatively small near the forest edge, where exchange with the external macroenvironment (represented by  $g_m$  and  $i_m$ ) directly constrains local conditions. This indicates that the parameterised macroenvironmental forcing is sufficient to capture first-order edge effects.

Further into the forest, discrepancies increase, with the largest slope occurring during nighttime at approximately 90 m from the edge, corresponding to a canopy gap. At this location, residuals clearly increase with wind speed. In the forest core, higher residuals are also observed at higher wind speeds, particularly during the day. This suggests that, while wind penetration is reduced, the simplified parameterisation of heat exchange between air, macroenvironment ( $g_m$ ,  $i_m$ ), soil ( $g_s$ ,  $i_s$ ), and forest structure ( $g_f$ ,  $i_f$ ) does not fully capture the complex and heterogeneous flow regimes that characterise dense forest interiors.

Across all locations, the largest residuals predominantly occur during daytime conditions and at intermediate wind speeds. However, these high residuals are mainly associated with a limited number of extreme values. In contrast, the majority of

daytime observations form a dense cluster with relatively small residuals, generally lower than those observed during nighttime periods, consistent with Fig. 6b.

Overall, these results indicate that the use of fixed convection parameters and distances of influence is sufficient to represent first-order macroenvironmental exchange at the forest edge, but insufficient to capture the spatial variability in wind-driven turbulence and mixing associated with canopy gaps and structurally complex forest interiors. At the same time, the weak sensitivity of residuals to wind speed suggests that explicitly resolving wind processes would likely lead to only incremental improvements under the conditions considered here.

Model–observation residual (mean error) in function of wind speed and distance to edge ( $D_e$ )

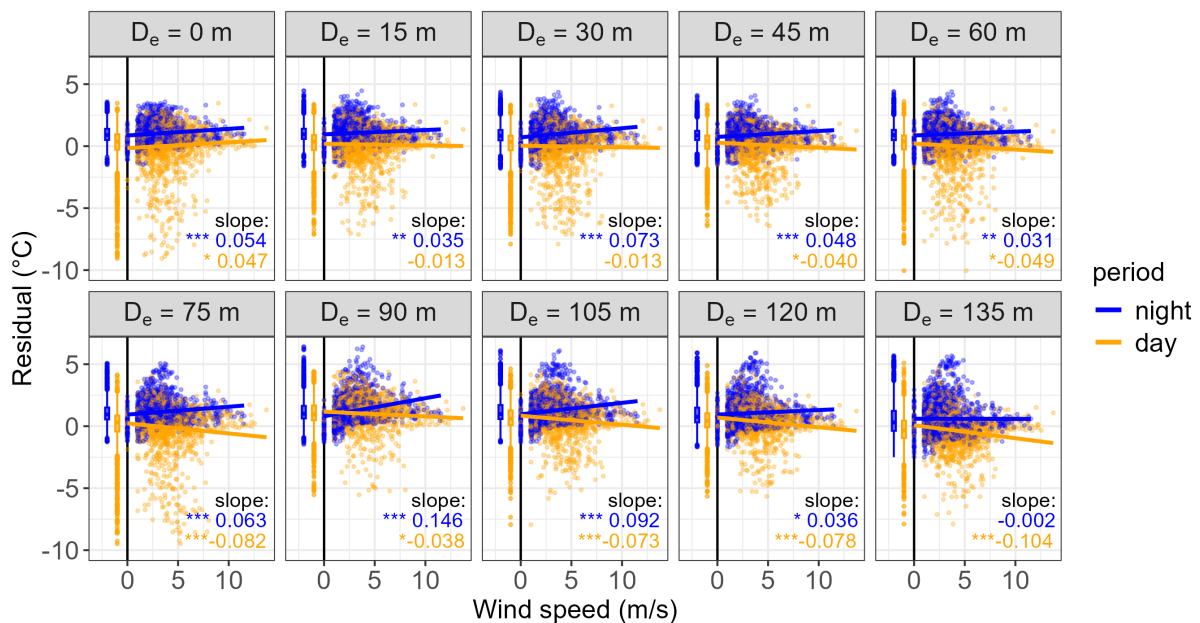


Figure 8: Relationship between model–observation residuals (mean error) and wind speed across distances from the forest edge to the forest core. Daytime hours are defined as 05:00–17:00 UTC and nighttime hours as 17:00–05:00 UTC. The dataset comprises the four seasons, represented by one month per season. Boxplots on the left side of each panel summarise the distribution of the data. Slopes of the linear relationships are indicated, with significance levels denoted as \*  $p < 0.05$ , \*\*  $p < 0.01$ , and \*\*\*  $p < 0.001$ , and no symbol indicating non-significant relationships.

Section 6.1 Dominant processes shaping simulated microclimates, Lines 761–772:

### 6.1 Dominant processes shaping simulated microclimates

The sensitivity analysis indicates that heat-transfer processes exert the strongest influence on both simulated air temperature and forest surface temperature within the forest transect. Parameters controlling the spatial influence of the macroenvironment and the soil surface, together with the soil conductance and forest–air convection, explained the majority of variance in modelled temperatures. These findings suggest that interactions with the external atmosphere and the soil surface constitute the dominant controls on local air and surface temperature patterns, particularly under conditions of strong thermal contrast between the forest and its surroundings. This interpretation is further supported by an additional analysis of model residuals, which

shows that discrepancies between modelled and observed temperatures increase with wind speed, particularly in open-canopy conditions such as forest gaps. This suggests that wind-driven turbulence and advective heat transport, which enhance atmospheric coupling, are not fully captured by the current parameterisation of heat exchange processes. At higher wind speeds, residuals also remain elevated in the forest interior, indicating that the simplified and spatially invariant parameterisation does not fully represent the complex flow regimes in dense canopy conditions.

Section 6.5 Model limitations and future development roadmap, Lines 877–886 and lines 915–924:

### **Key limitations**

Several limitations arise from the simplified representation of physical processes in the current model version.

First, canopy–atmosphere exchange processes are only partially represented. Wind-driven turbulence, advection, and momentum transfer are not explicitly simulated, although these processes play a key role in shaping forest microclimates, particularly at forest edges (Chen et al., 1995; De Frenne et al., 2021). Sensible heat exchange is parameterised using a bulk heat transfer coefficient, and evapotranspiration is represented using a Priestley–Taylor formulation, which assumes radiation-driven latent heat fluxes and neglects explicit aerodynamic control. While this assumption is often reasonable for forest interior conditions, it may be less appropriate near forest edges where horizontal advection of heat and moisture can modify evaporative demand. This limitation is also reflected in the residual analysis, which indicates that model–observation discrepancies increase under higher wind speeds, particularly in structurally open areas where atmospheric coupling is enhanced.

[ . . . ]

### **Future development roadmap**

These limitations define a clear roadmap for future model development (Fig. 10).

A first priority is to improve the representation of canopy–atmosphere exchange by incorporating wind-dependent aerodynamic processes. This can be achieved within the existing voxel-based framework by linking the current bulk heat transfer coefficients ( $g_m$ ,  $g_s$ ,  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ ,  $i_f$ ) to wind speed and canopy structural properties (Maurer et al., 2013; Kimura et al., 2020; Flayyih Al-Rikabi et al., 2024). Such an extension would allow turbulent mixing and advective heat transport to be represented more explicitly, while retaining the current parameterisation structure. Extending the evapotranspiration formulation to a Penman–Monteith framework would further enable explicit representation of canopy resistance and atmospheric demand, and facilitate the inclusion of humidity-related state variables such as vapour pressure deficit and relative humidity.

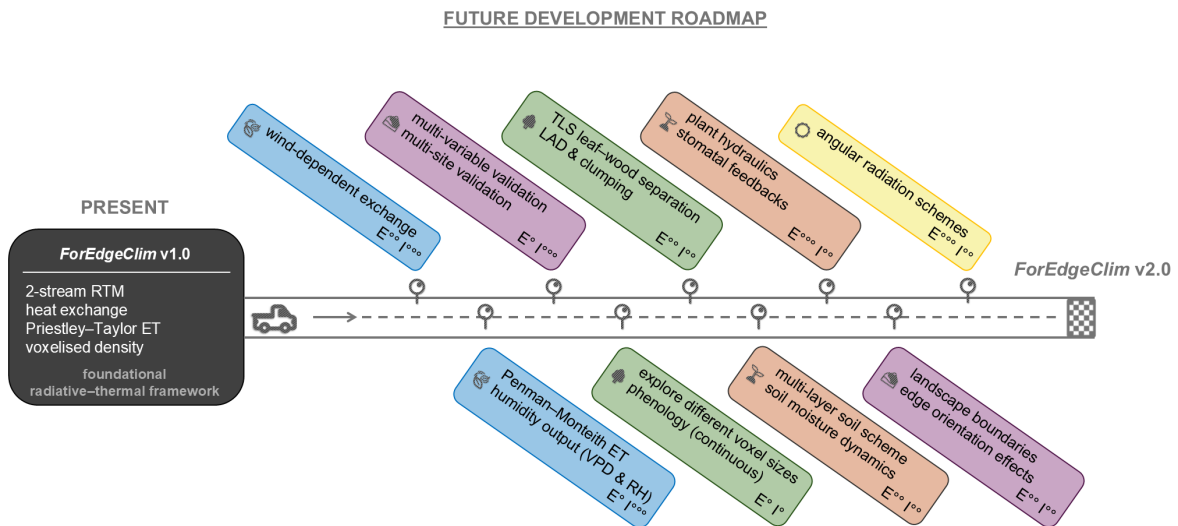


Figure 10: Conceptual development roadmap for the *ForEdgeClim* radiative-thermal core, illustrating the progression from the current model formulation (present) towards a target fully coupled three-dimensional microclimate model. The road visualisation represents a continuous development trajectory along which key model extensions are introduced, including atmospheric coupling (blue), improved boundary conditions and validation (purple), canopy structure refinement (green), soil-plant interactions (brown), and advanced radiation schemes (yellow). For each extension, the expected implementation effort (E) and potential model impact (I) are indicated using a qualitative rating, where the number of symbols (°) reflects relative magnitude (e.g., E° denotes low effort, I°°° denotes high impact).

### Reviewer 2 Comment 3

Lack of leaf-wood separation:

The model assigns a single bulk density ( $\rho$ ) to each voxel and applies uniform optical properties ( $\omega$ ,  $\beta$ ,  $\beta_0$ ) across all structural elements, without distinguishing leaves from woody material. This is acknowledged in Table A5 but receives almost no discussion in the main text.

This simplification has cascading physical consequences: Shortwave scattering properties of leaves and wood differ substantially, particularly in the near-infrared band. A single scattering coefficient  $\omega$  cannot accurately represent both. Only leaves transpire, yet the Priestley-Taylor LE is applied to the entire "forest surface." In winter for this deciduous forest (oak, beech, ash), the canopy is essentially bare wood, but the model continues to compute LE as if transpiring surfaces are present. Voxel densities are scaled monthly using PAI ratios, but optical properties are held constant year-round (Table A5). In a deciduous forest, the transition from leaf-on to leaf-off fundamentally changes the scattering regime – this is not captured. I could list more, but i just stop here. Seperate leaf and wood component is critical, even in CLM, which is at far coarser spatial resolution, it maintains separate optical properties for leaves and stems ( $\rho_l / \rho_s$ ,  $\tau_l / \tau_s$ , etc.) and weights them by their respective area fractions (LAI and SAI) before entering the two-stream calculation.

What makes this particularly notable is that the TLS data used in this study are among the most suitable data sources currently available for leaf-wood separation at fine scales. Established methods exist for classifying TLS point clouds into leaf and wood components using local geometric features (planarity, linearity), return intensity, or machine learning approaches. Moreover, the co-author team includes leading expertise in TLS-based forest structural analysis, and the model's RTM is based on *ED2.2*, which explicitly separates leaf and wood area indices with distinct optical properties.

**Response:**

We agree that leaves and woody elements have distinct optical and physiological properties and that separating leaf and wood components can improve the physical realism of radiative transfer and evapotranspiration modelling. In particular, the reviewer correctly notes that leaves and woody elements differ in their scattering behaviour and that transpiration is primarily associated with foliage rather than woody surfaces.

In the current version of *ForEdgeClim*, canopy structure is represented using a bulk voxel density ( $\rho$ ) derived from TLS data and scaled using plot-level plant area index (PAI). Within each voxel, vegetation elements are therefore treated as a homogeneous turbid medium. We agree that separating leaf and woody components is both feasible and important, particularly when using TLS data that can support such distinctions. In this first model version, however, we deliberately adopted a minimal structural parameterisation to establish a computationally tractable baseline framework and to enable a well-constrained calibration and sensitivity analysis.

Importantly, the current model architecture is fully compatible with a leaf–wood separation, and such an extension can be implemented without fundamental changes to the voxel-based framework. We therefore consider the explicit representation of foliage and woody components, including distinct optical and physiological properties, a key priority for future model development.

In response to the reviewer’s comment, we have introduced a seasonal differentiation in canopy optical properties by defining separate parameter sets for leaf-on and leaf-off conditions (Table A5), including distinct values for  $\omega$ ,  $\beta$ , and  $\beta_0$ . The selection between leaf-on and leaf-off parameter sets is prescribed based on the season of the input data, with leaf-off conditions applied from November to March and leaf-on conditions during the remainder of the year. This modification allows the model to capture first-order seasonal changes in canopy radiative behaviour associated with the presence or absence of foliage. We note that this update did not result in observable changes to the results presented in this study. Although the model was applied across four seasonal datasets, only the winter period (January 2025) is affected by this modification, as the other seasons were already represented using leaf-on conditions. Even for the winter dataset, the impact of the updated optical parameters remains very limited. This is consistent with the sensitivity analysis, which shows that shortwave radiative transfer parameters have a relatively small influence on simulated air temperature. Consequently, no visible differences in air temperature patterns were observed following this modification. We note, however, that changes in canopy optical properties do have a stronger influence on light availability and interception, as illustrated in Fig. R1 (included in this response). We further note that small numerical differences between model runs can arise due to stochastic components in the sensitivity analysis and optimisation procedures. These differences are of similar magnitude to the effect of the present modification and do not affect the interpretation of the results.

We note, however, that the model still does not explicitly distinguish between leaf and woody components within individual voxels. As such, it does not resolve the simultaneous presence of leaves and woody elements, nor does it explicitly restrict transpiration to foliage. The current approach should therefore be interpreted as a simplified representation of seasonal canopy states rather than a fully mechanistic separation of structural components.

As suggested by the reviewer, explicitly separating leaf and wood components would provide a more mechanistic representation of canopy radiative transfer and evapotranspiration processes.

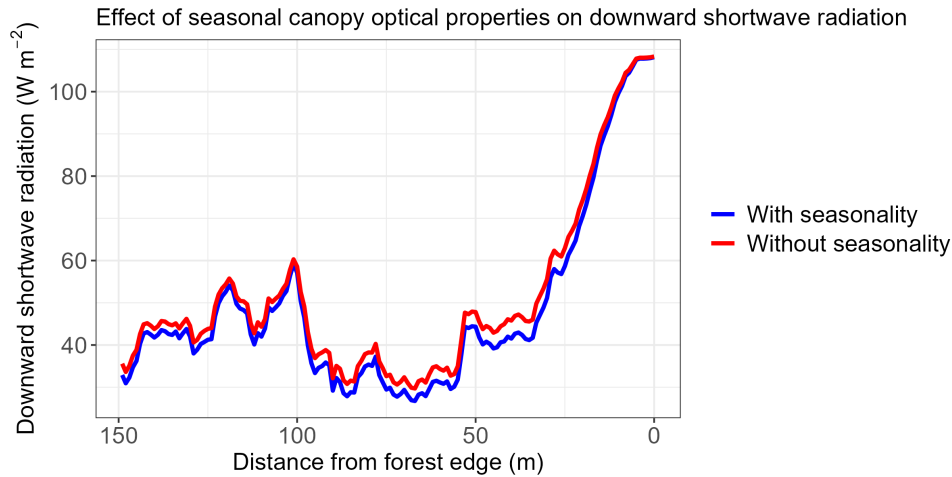


Figure R1: Effect of seasonal canopy optical properties (leaf-on versus leaf-off parameterisation) on downward shortwave radiation for a winter case (15 January 2025, 12:00 UTC). The figure shows the mean downward shortwave radiation averaged over all north–south slices, plotted along the east–west transect line.

However, we note that leaf–wood separation from TLS data is itself an active research field, with a range of methodological approaches and associated uncertainties. Implementing such a distinction would therefore introduce additional sources of uncertainty related to classification accuracy and structural parameterisation, which are beyond the scope of the current model version.

At the same time, implementing such a distinction would require substantial extensions to the current modelling framework, including separating leaf and woody elements within the voxel grid, assigning distinct optical and physiological properties, and adapting both the radiative transfer and heat exchange formulations accordingly. Such developments would increase model complexity, parameter requirements, and computational demand, and are therefore left for future work.

The TLS data used in this study indeed provide opportunities for more detailed structural characterisation. Future versions of *ForEdgeClim* could incorporate leaf–wood separation within the voxel grid, allowing the radiative transfer model to assign distinct optical properties to foliage and woody elements and enabling evapotranspiration to be linked more explicitly to foliage distribution.

In response to the reviewer’s comment, the manuscript was revised to more clearly acknowledge the current bulk representation of canopy structure, while incorporating a first-order seasonal differentiation in optical properties (leaf-on/leaf-off) and expanding the discussion on the implications of not explicitly separating leaf and woody components.

Section 6.5 Model limitations and future model development roadmap, Lines 887–897 and lines 925–936:

### Key limitations

[...]

Second, the representation of canopy structure is simplified. Vegetation elements within each voxel are treated as a bulk medium using a structural density ( $\rho$ ), without explicit separation of foliage and woody components. While the voxel-based representation derived from TLS data captures large-scale structural heterogeneity and gap fraction variability, sub-voxel variability (e.g., leaf area density profiles or canopy clumping)

is not explicitly resolved. In addition, although seasonal variation in canopy density is partially represented through PAI scaling, optical properties are simplified and only represented at a coarse seasonal level (leaf-on versus leaf-off), which may not fully capture transitional phenological dynamics. In addition, the representation of canopy structure is inherently dependent on the chosen voxel resolution. While a 1 m resolution was adopted in this study as a compromise between structural detail and computational efficiency, changes in spatial resolution may alter the representation of canopy heterogeneity and thereby influence radiative transfer and heat exchange processes. The sensitivity of model results to voxel resolution was not evaluated in the current study and remains an important source of structural uncertainty.

[...]

### **Future development roadmap**

[...]

A second development pathway concerns structural refinement of the canopy representation. This could be implemented by partitioning voxel-level density into leaf and woody components, allowing distinct optical and physiological properties to be assigned within each voxel while preserving the existing spatial discretisation. Incorporating TLS-based leaf–wood separation and voxel-level structural metrics (e.g., leaf area density or clumping indices) would improve the representation of radiative transfer and evapotranspiration processes, similar to approaches used in ecosystem models such as *ED2.2* (Longo et al., 2019) and *DART* (Gastellu-Etchegorry et al., 2004). While seasonal variation in optical properties is already represented through leaf-on and leaf-off parameter sets, further developments could enable a more continuous and mechanistic representation of phenological transitions. In addition, the choice of voxel resolution is closely linked to the representation of canopy structure. While the current study adopts a 1 m resolution, changes in spatial resolution directly affect how structural heterogeneity is represented within the voxel grid, with potential implications for radiative transfer, heat exchange, and parameter sensitivity. Future work should therefore systematically evaluate the influence of voxel resolution on model behaviour and performance, in order to guide scale-aware application of the model.

Appendix Table A5:

**Table A5.** Assumptions and limitations of the two-stream RTM in *ForEdgeClim*.

- ◇ Voxel density does not distinguish between leaf and wood, or between tree species.
- ◇ No spectral variation within both the shortwave and longwave band.
- ◇ Optical properties are spatially uniform and represented using two seasonal parameter sets (leaf-on and leaf-off), without resolving leaf and woody components within voxels.
- ◇ The longwave RTM assumes a constant emissivity across all forest surfaces.
- ◇ The canopy is assumed to have a spherical leaf angle distribution.

#### Reviewer 2 Comment 4

Temperature-only output for a model framed as a "microclimate model":

*ForEdgeClim* predicts only temperature (air, surface, soil), yet in the microclimate literature, humidity (vapour pressure deficit, relative humidity) is widely recognised as a co-driver of ecological processes, species distributions, and evaporative demand. The Priestley-Taylor formulation implicitly involves humidity through the psychrometric constant, but no humidity state variable is tracked or output. For a model positioned for ecological applications (Section 6.7), this is a meaningful gap. I would like to see more discussions about whether a diagnostic humidity estimate could be derived from the existing framework. If humidity prediction is planned for a future version, state this clearly and outline how it would be implemented.

#### Response:

We agree that humidity-related variables such as vapour pressure deficit (VPD) and relative humidity (RH) are important components of forest microclimates and play a key role in ecological processes and plant physiological responses. In the current version of *ForEdgeClim*, the model focuses on simulating temperature dynamics (air, surface, and soil temperature) as a first step towards resolving spatial microclimate gradients within structurally complex forest environments. At present, this focus is also constrained by data availability, as only temperature measurements are available for model development and evaluation.

Humidity is not currently represented as an explicit state variable in the model. Instead, the latent heat flux formulation relies on the Priestley–Taylor approach, which implicitly accounts for atmospheric moisture conditions through the psychrometric constant ( $\alpha$ , dimensionless) but does not explicitly simulate humidity dynamics within the canopy airspace.

We agree that incorporating humidity variables such as RH or VPD would substantially improve the ecological applicability of the model. In future model developments, humidity could be introduced as an additional state variable within the voxel grid, allowing the model to simulate spatial variation in vapour pressure and VPD. This would enable tighter coupling between energy balance processes and plant physiological responses.

In particular, the planned extension of the latent heat flux formulation towards a Penman–Monteith-based approach would naturally incorporate atmospheric moisture demand through VPD and canopy resistance. Such an extension would provide a more mechanistic representation of evapotranspiration processes and would enable the model to output humidity-related microclimate variables relevant for ecological applications.

In response to the reviewer's suggestion, the manuscript was revised to clarify that the current model version focuses on temperature dynamics and does not explicitly simulate humidity variables such as VPD or RH. More precisely, the discussion section 6.5 was expanded to outline potential future developments in which humidity is introduced as an additional state variable within the voxel framework and coupled to evapotranspiration processes through a Penman–Monteith formulation. For this expansion of Section 6.5, we refer to our answer on your earlier comment (comment 2).

#### Reviewer 2 Comment 5

Calibration only against air temperature, leaving surface temperature unconstrained:

Calibration is performed exclusively against air temperature from TOMST sensors at 15 cm height, yet forest surface temperature is a key prognostic variable (Figs. 2c, 4b). The Sobol analysis reveals that  $g_f$  dominates surface temperature variance (8.7-32%) but is excluded from calibration because air temperature is insensitive to it. This means surface temperature predictions are essentially unconstrained by observations. I would suggest adding an uncertainty envelope for surface temperature predictions based on the parameter ensemble spread from the Sobol analysis; also could discuss what observational data (e.g., thermal cameras, radiometers) would be needed for proper surface temperature validation.

#### Response:

We agree that forest surface temperature is an important prognostic variable within the model, as it directly influences sensible and latent heat fluxes and therefore affects the simulated microclimate temperature field. In the current study, calibration was performed using air temperature observations from TOMST sensors located at 15 cm height, as these measurements directly represent the microclimate variable that the model is primarily designed to reproduce. In addition, these sensors were the primary measurements available across the study site, which guided the choice of calibration data.

Surface temperature in *ForEdgeClim* is not intended to represent a directly observable canopy surface temperature, but rather an effective temperature representing the aggregated energy balance of vegetation elements within each voxel. As a result, direct observational constraints for this variable are not readily available within the current dataset.

We agree that the Sobol sensitivity analysis indicates that the sensible heat exchange coefficient ( $g_f$ ) has a strong influence on surface temperature while having a more limited influence on air temperature. This reflects the role of surface temperature as an intermediate variable in the energy balance rather than the primary calibration target. To provide insight into the resulting uncertainty in modelled surface temperatures, we now include an uncertainty envelope derived from the parameter ensemble used in the Sobol sensitivity analysis. Specifically, for each model condition we compute the distribution of simulated surface temperatures across the parameter ensemble. This allows readers to assess the range of surface temperature outcomes that arise from parameter uncertainty.

We agree with the reviewer that additional observations could improve the evaluation of surface temperature dynamics. For example, thermal infrared measurements from canopy radiometers or thermal cameras could provide useful constraints for validating the modelled surface energy balance. The discussion was expanded to clarify that model calibration was performed using air temperature observations because the model is primarily designed to reproduce microclimate air temperatures. In addition, we now explicitly acknowledge that surface temperature predictions are less directly constrained by observations and highlight the potential use of thermal infrared measurements (e.g., canopy radiometers or thermal cameras) for future model validation.

Section 4.2.2 Validation (part of Section 4 Model evaluation), Lines 520–522:

In addition, to evaluate the uncertainty associated with forest surface temperature

predictions, the Sobol parameter ensemble was propagated through the model, and the resulting distributions of simulated surface temperature were analysed across all validation conditions.

Section 5.3.4 Uncertainty in forest surface temperature predictions (part of Section 5 Results), Lines 741–753:

#### **5.3.4 Uncertainty in forest surface temperature predictions**

To assess the implications of parameter uncertainty for forest surface temperature, the Sobol parameter ensemble was propagated through the model, and the resulting distributions of simulated surface temperature were analysed across all conditions along both the horizontal and vertical transect lines (resp. Fig. 9 and appendix Fig. C6). The resulting distributions are approximately bell-shaped, indicating a smooth and stable model response to parameter variation, without evidence of abrupt thresholds or regime shifts. However, the width of these distributions varies substantially between conditions, demonstrating that forest surface temperature remains weakly constrained in several cases, with the central 95 % range spanning approximately 0.02–11.29 °C for the horizontal transect line and 0.02–4.05 °C for vertical transect line.

This behaviour is consistent with the Sobol sensitivity analysis, which identified the forest heat transfer parameter  $g_f$  as a dominant contributor to surface temperature variance (8.7–32 %). As  $g_f$  does not influence air temperature and is therefore not constrained during calibration, its variability directly translates into uncertainty in surface temperature predictions.

The resulting uncertainty envelopes thus provide a quantitative measure of this lack of constraint and highlight the need for additional observational constraints to better resolve surface energy exchange processes.

Section 6.5: Model limitations and future developments, Lines 905–907 and lines 942–949:

#### **Key limitations**

[...]

Fourth, model evaluation is constrained by the available observations. Calibration and validation are primarily based on air temperature measurements, which represent the main target variable of the model. As a consequence, surface temperatures and individual energy balance components are less directly constrained by observations.

[...]

#### **Future development roadmap**

[...]

A fourth development direction is to improve boundary condition realism and model evaluation. Incorporating spatially explicit representations of adjacent land-use types would allow edge effects to be simulated more realistically across heterogeneous landscapes. In addition, future studies could include multi-variable validation using surface temperature, humidity, and radiative flux measurements. In particular, the inclusion of thermal infrared observations, such as canopy radiometers or thermal imaging cameras,

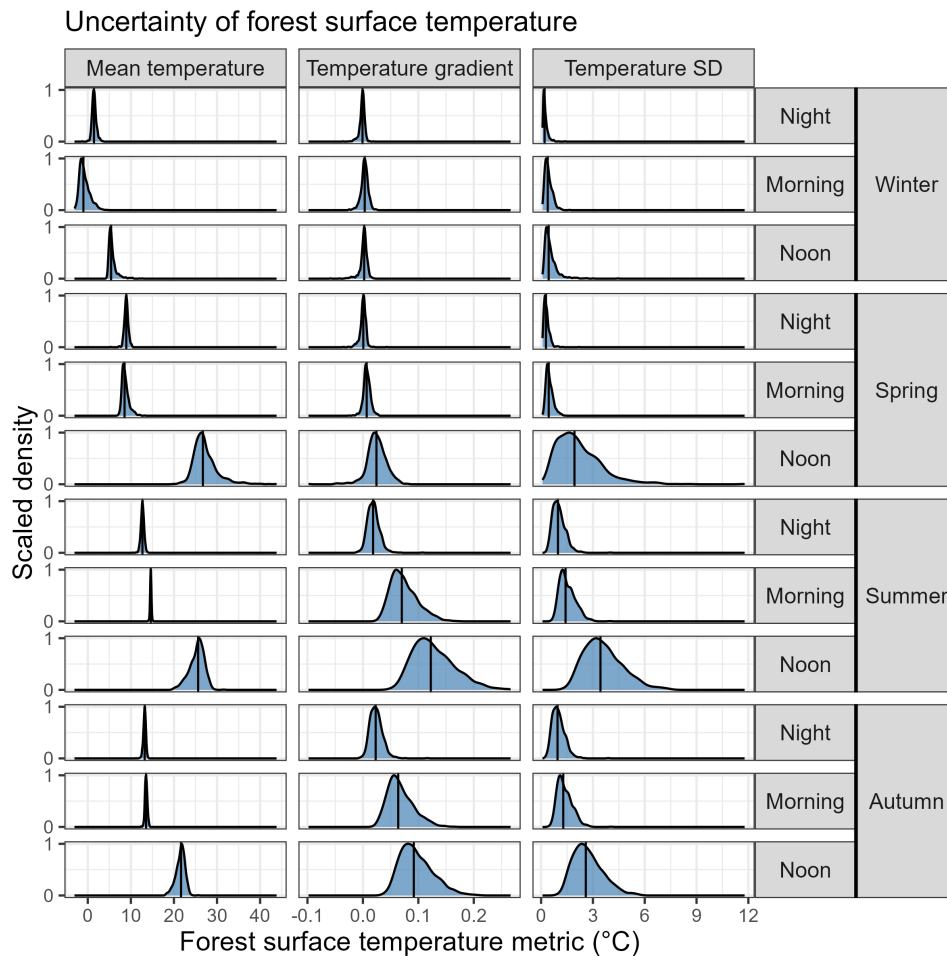


Figure 9: Uncertainty in forest surface temperature along the horizontal transect derived from the Sobol parameter ensemble. Density curves are scaled (peaks are set to a value of 1) to facilitate comparison of distribution shapes. Vertical lines indicate median values.

would enable direct validation of forest surface temperature and provide constraints on surface energy balance processes, thereby reducing uncertainty associated with parameters that primarily control surface temperature dynamics. Sensitivity analyses exploring edge orientation effects could further improve understanding of directional microclimate responses.

**Reviewer 2 Comment 6**

The future development roadmap needs to be concrete and specific:

Section 6.5 identifies several missing processes: wind, improved soil heat flux, advanced radiative transfer, but presents them as vague aspirations ("future work could...") without any technical specificity. Given how fundamental some of these missing components are, this is insufficient for a v1.0 model description paper. Readers and potential users need to assess whether *ForEdgeClim* has a viable path toward becoming the comprehensive tool it aspires to be, or whether its current architecture would require fundamental restructuring.

**Response:**

We agree that the original manuscript did not sufficiently specify how several missing processes

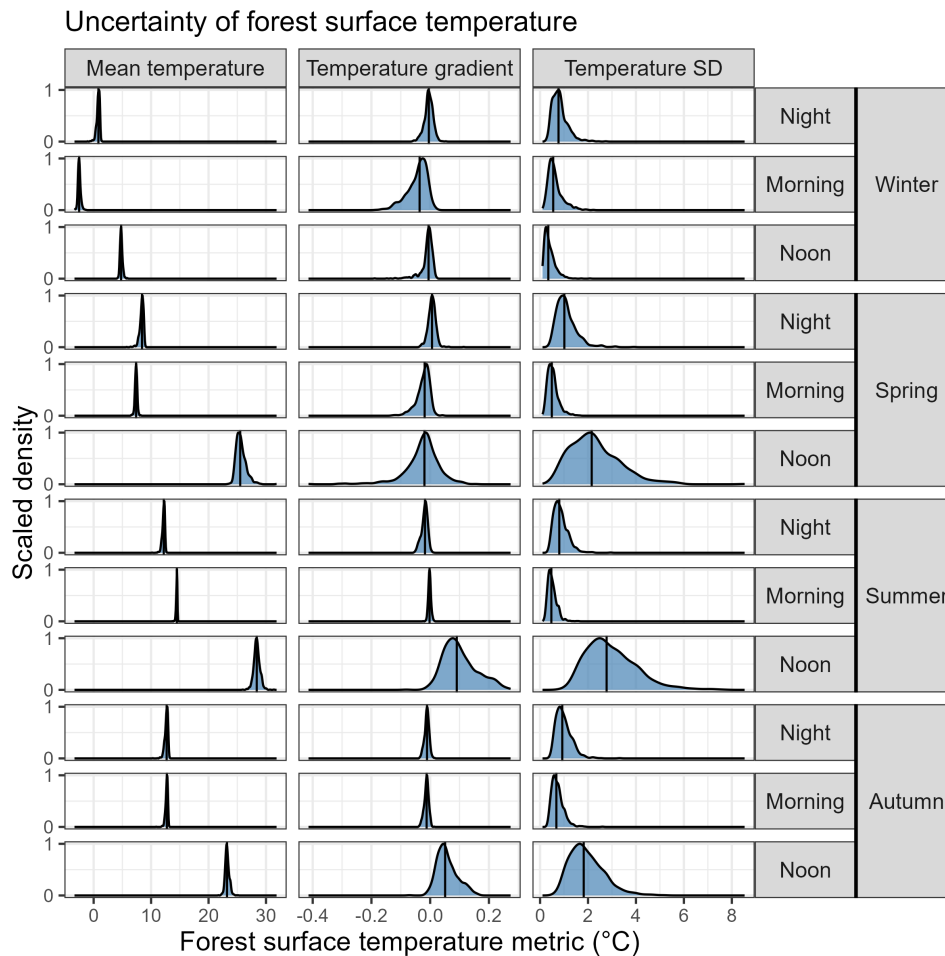


Figure C6: Uncertainty in forest surface temperature along the vertical transect derived from the Sobol parameter ensemble. Density curves are scaled (peaks are set to a value of 1) to facilitate comparison of distribution shapes. Vertical lines indicate median values.

could be incorporated into future versions of *ForEdgeClim*. As suggested by the reviewer, providing a clearer and more technically specific development trajectory is important for assessing the model’s extensibility.

In response, Section 6.5 has been substantially revised to provide a more explicit and structured roadmap. In particular, we now describe how each major process can be integrated within the existing voxel-based framework. For example, wind-driven processes can be incorporated by making the current bulk heat transfer coefficients ( $g_m$ ,  $g_s$ ,  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ ,  $i_f$ ) functions of wind speed and canopy properties, thereby extending the current parameterisation rather than replacing it. Similarly, soil heat exchange can be extended by replacing the current single-layer formulation with a multi-layer scheme operating on the same voxel grid, and canopy structural refinement can be implemented by subdividing voxel density into leaf and woody components without altering the spatial discretisation.

These examples clarify that the proposed developments build directly on the existing model structure and do not require fundamental restructuring of the voxel-based framework. The revised roadmap therefore demonstrates that *ForEdgeClim* v1.0 provides a viable and extensible foundation for progressively more mechanistic microclimate modelling.

## 6.5 Model limitations and future development roadmap

### Current model formulation

*ForEdgeClim* v1.0 represents forest microclimates using a spatially explicit three-dimensional voxel framework that resolves radiative and thermal energy exchange processes within complex canopy structures derived from TLS data. The model explicitly simulates shortwave and longwave radiative transfer, evapotranspiration, and sensible heat exchange, and is designed to reproduce spatial temperature gradients along forest edge-to-core transitions.

This modelling approach reflects a balance between physical realism and computational tractability, allowing key microclimate processes to be represented mechanistically while remaining applicable to high-resolution forest structure data. External macro-climatic forcing is prescribed based on observed meteorological data, and canopy structure is represented using voxel-level density derived from TLS measurements and scaled using plant area index (PAI).

### Key limitations

Several limitations arise from the simplified representation of physical processes in the current model version.

First, canopy–atmosphere exchange processes are only partially represented. Wind-driven turbulence, advection, and momentum transfer are not explicitly simulated, although these processes play a key role in shaping forest microclimates, particularly at forest edges (Chen et al., 1995; De Frenne et al., 2021). Sensible heat exchange is parameterised using a bulk heat transfer coefficient, and evapotranspiration is represented using a Priestley–Taylor formulation, which assumes radiation-driven latent heat fluxes and neglects explicit aerodynamic control. While this assumption is often reasonable for forest interior conditions, it may be less appropriate near forest edges where horizontal advection of heat and moisture can modify evaporative demand. This limitation is also reflected in the residual analysis, which indicates that model–observation discrepancies increase under higher wind speeds, particularly in structurally open areas where atmospheric coupling is enhanced.

Second, the representation of canopy structure is simplified. Vegetation elements within each voxel are treated as a bulk medium using a structural density ( $\rho$ ), without explicit separation of foliage and woody components. While the voxel-based representation derived from TLS data captures large-scale structural heterogeneity and gap fraction variability, sub-voxel variability (e.g., leaf area density profiles or canopy clumping) is not explicitly resolved. In addition, although seasonal variation in canopy density is partially represented through PAI scaling, optical properties are simplified and only represented at a coarse seasonal level (leaf-on versus leaf-off), which may not fully capture transitional phenological dynamics. In addition, the representation of canopy structure is inherently dependent on the chosen voxel resolution. While a 1 m resolution was adopted in this study as a compromise between structural detail and computational efficiency, changes in spatial resolution may alter the representation of canopy heterogeneity and thereby influence radiative transfer and heat exchange

processes. The sensitivity of model results to voxel resolution was not evaluated in the current study and remains an important source of structural uncertainty.

Third, the representation of subsurface and ecohydrological processes is limited. Soil heat exchange is represented using a simplified conductive formulation with a shallow reference layer, and the model assumes quasi-steady-state conditions for each simulated time step. As a result, temporal heat storage and the characteristic phase lag between surface forcing and subsurface heat flux are not explicitly resolved (Campbell and Norman, 2000). In addition, water transport processes and plant hydraulics are not currently represented. Feedbacks between soil moisture, plant water status, and energy exchange – such as stomatal regulation of transpiration – are therefore not captured, which may influence microclimate dynamics under water-limited conditions.

Fourth, model evaluation is constrained by the available observations. Calibration and validation are primarily based on air temperature measurements, which represent the main target variable of the model. As a consequence, surface temperatures and individual energy balance components are less directly constrained by observations.

Finally, the representation of the external macroenvironment is simplified. Boundary conditions are derived from standard meteorological observations over short grass following World Meteorological Organization guidelines (WMO, 2021). This implicitly assumes homogeneous surrounding land cover, whereas adjacent land-use types (e.g., cropland or urban areas) can differ substantially in albedo, roughness, heat storage, and moisture availability, thereby influencing lateral radiative and thermal fluxes at forest edges (Chen et al., 1993; De Frenne et al., 2021). In addition, while solar geometry is represented, the sensitivity of simulated microclimates to alternative edge orientations was not systematically explored, despite its known influence on edge microclimate gradients (Chen et al., 1995).

### **Future development roadmap**

These limitations define a clear roadmap for future model development (Fig. 10).

A first priority is to improve the representation of canopy–atmosphere exchange by incorporating wind-dependent aerodynamic processes. This can be achieved within the existing voxel-based framework by linking the current bulk heat transfer coefficients ( $g_m$ ,  $g_s$ ,  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ ,  $i_f$ ) to wind speed and canopy structural properties (Maurer et al., 2013; Kimura et al., 2020; Flayyih Al-Rikabi et al., 2024). Such an extension would allow turbulent mixing and advective heat transport to be represented more explicitly, while retaining the current parameterisation structure. Extending the evapotranspiration formulation to a Penman–Monteith framework would further enable explicit representation of canopy resistance and atmospheric demand, and facilitate the inclusion of humidity-related state variables such as vapour pressure deficit and relative humidity.

A second development pathway concerns structural refinement of the canopy representation. This could be implemented by partitioning voxel-level density into leaf and woody components, allowing distinct optical and physiological properties to be assigned within each voxel while preserving the existing spatial discretisation. Incorporating TLS-based leaf–wood separation and voxel-level structural metrics (e.g., leaf area density or clumping indices) would improve the representation of radiative transfer and evapotranspiration processes, similar to approaches used in ecosystem models such as *ED2.2* (Longo et al., 2019) and *DART* (Gastellu-Etchegorry et al., 2004). While

seasonal variation in optical properties is already represented through leaf-on and leaf-off parameter sets, further developments could enable a more continuous and mechanistic representation of phenological transitions. In addition, the choice of voxel resolution is closely linked to the representation of canopy structure. While the current study adopts a 1 m resolution, changes in spatial resolution directly affect how structural heterogeneity is represented within the voxel grid, with potential implications for radiative transfer, heat exchange, and parameter sensitivity. Future work should therefore systematically evaluate the influence of voxel resolution on model behaviour and performance, in order to guide scale-aware application of the model.

A third priority is the integration of soil and plant water dynamics. Implementing a multi-layer soil heat and water balance scheme would explicitly represent vertical heat diffusion and soil moisture dynamics, building on the current vertical heat exchange formulation within the voxel grid. Coupling this with a plant hydraulic framework would enable feedback between soil moisture, plant water status, and stomatal conductance, thereby improving the representation of evapotranspiration and energy partitioning under varying environmental conditions.

A fourth development direction is to improve boundary condition realism and model evaluation. Incorporating spatially explicit representations of adjacent land-use types would allow edge effects to be simulated more realistically across heterogeneous landscapes. In addition, future studies could include multi-variable validation using surface temperature, humidity, and radiative flux measurements. In particular, the inclusion of thermal infrared observations, such as canopy radiometers or thermal imaging cameras, would enable direct validation of forest surface temperature and provide constraints on surface energy balance processes, thereby reducing uncertainty associated with parameters that primarily control surface temperature dynamics. Sensitivity analyses exploring edge orientation effects could further improve understanding of directional microclimate responses.

Finally, advances in radiative transfer modelling could be explored within the current framework by replacing or complementing the two-stream approximation with more detailed angular radiation schemes, such as discrete ordinates methods (Stamnes et al., 1988), spherical harmonics expansions (Modest and Lei, 2012), or Monte Carlo ray tracing approaches (Disney et al., 2000), where computationally feasible.

Together, these developments illustrate that *ForEdgeClim* v1.0 should be viewed as an initial modelling framework. The current radiative–thermal formulation provides a flexible basis upon which progressively more mechanistic representations of canopy microclimate processes can be integrated, without requiring fundamental restructuring of the voxel-based architecture. This design enables the model to evolve towards a more comprehensive three-dimensional microclimate modelling system for heterogeneous forest landscapes.

## 2.3 Minor comments

### Reviewer 2 Comment 7

400 Latin hypercube samples for 25 parameters may yield unreliable higher-order Sobol indices. Convergence of total-order indices typically requires substantially more samples. I would suggest report confidence bounds on the Sobol indices, or run a convergence check (e.g., 200 vs. 400 samples) to demonstrate stability.

### Response:

We agree that estimating Sobol indices for models with a relatively large number of parameters can require substantial sample sizes, particularly when higher-order interactions are of interest. In the present study, the Sobol analysis was primarily used as a screening tool to identify the parameters that most strongly influence model outputs and to guide the calibration procedure.

Our interpretation of the sensitivity results therefore focuses on the relative importance of parameters based on first-order and total-order indices rather than on higher-order interaction effects. We acknowledge that the number of samples used represents a trade-off between computational cost and statistical robustness, given the computational expense of the 3D voxel-based simulations.

In response to the reviewer's suggestion, the manuscript was revised to report confidence intervals for the Sobol indices of the most influential parameters on air temperature, defined as those explaining more than 65 % of the model output variance, to provide an indication of the uncertainty associated with these estimates.

Furthermore, we performed an additional convergence analysis by comparing Sobol indices obtained from different sample sizes (200 and 400 Latin hypercube samples). This analysis showed that the ranking and magnitude of the most influential parameters remain stable across sample sizes, supporting the robustness of the sensitivity results for the purpose of parameter screening. The results of this convergence check are now included in the revised manuscript.

Section 5.2 Sensitivity analysis, Lines 567–571, lines 584–588, and lines 607–612:

The sensitivity patterns for air temperature reveal a strong dependence on three heat-transfer parameters:  $i_m$ ,  $i_s$ , and  $k_s$ , representing the distance of influence from the macroenvironment, the distance of influence from the soil surface, and the soil conductance, respectively (Fig. 4a). Across all conditions, these parameters together account for 67–76 % of the total output variance along the horizontal transect. On average, their combined contribution amounts to 70.8 % (95 % CI: 68.4–73.2 %), indicating that model sensitivity is consistently concentrated within a small subset of parameters.

[...]

When performing the same analysis for both air temperature and forest surface temperature along the vertical line, we observed consistent patterns (appendix Fig. C3). For air temperature (appendix Fig. C3a), the parameters  $i_m$ ,  $i_s$ , and  $k_s$  dominate model sensitivity, together explaining 67–72 % of the total model output variance. On average, their combined contribution amounts to 70.3 % (95 % CI: 68.0–72.5 %), again, indicating that model sensitivity is consistently concentrated within a small subset of parameters.

[...]

To assess the robustness of the Sobol sensitivity indices, a convergence analysis was performed by comparing results obtained with 200 and 400 Latin hypercube samples (appendix Fig. C4). The total-order Sobol indices of the dominant parameters for both air temperature ( $i_m$ ,  $i_s$ , and  $k_s$ ) and forest surface temperature ( $i_m$ ,  $i_s$ , and  $g_f$ ), as well as their combined contribution, showed only minor differences between the two sample sizes when averaged across all conditions (i.e., seasons, times of day, and metrics) along both horizontal and vertical transects. This indicates that the sensitivity estimates are stable and sufficiently converged for the purpose of identifying the main drivers of model variability.

Appendix Fig. C4:

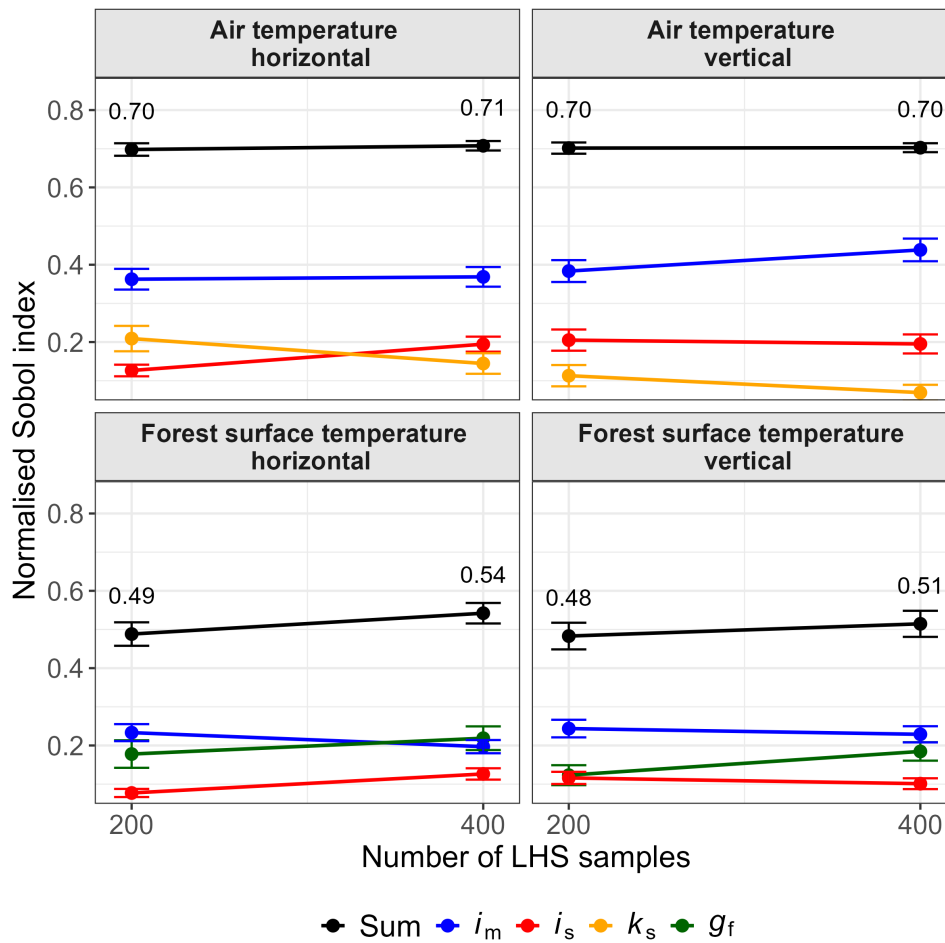


Figure C4: Convergence of Sobol sensitivity indices with increasing sample size. Total-order indices are shown for the most influential parameters for both air temperature ( $i_m$ ,  $i_s$ , and  $k_s$ ) and forest surface temperature ( $i_m$ ,  $i_s$ , and  $g_f$ ), as well as their combined contribution (Sum), based on 200 and 400 Latin hypercube samples (LHS). Here,  $i_m$  and  $i_s$  represent the distance of influence from the macroenvironment and from the soil surface, respectively,  $k_s$  denotes soil conductance, and  $g_f$  the bulk convection coefficient between air and the forest surface. Values represent averages across all conditions (i.e., seasons, times of day, and metrics) for both air temperature and forest surface temperature, along horizontal and vertical transects. Notably, for air temperature, the combined contribution of the most influential parameters – on which the model calibration is based – remains nearly unchanged when increasing the sample size from 200 to 400, indicating strong convergence of the key drivers. The stability in both ranking and magnitude further supports the robustness of the sensitivity analysis for parameter screening. Error bars indicate the standard error of the mean Sobol index across all conditions.

**Reviewer 2 Comment 8**

The convergence of  $k_s$  and  $i_m$  to their upper bounds in multiple calibrations is acknowledged but attributed only to overly restrictive priors. However, a parameter hitting its bound may also indicate structural model misspecification: a missing process being compensated by inflated parameter values (e.g.,  $i_m$  compensating for absent wind-driven advection). Both interpretations should be discussed.

**Response:**

We agree that parameters converging to their bounds can reflect multiple possible causes. In the original manuscript, we primarily discussed the possibility that the prior parameter ranges were too restrictive. However, as the reviewer correctly points out, such behaviour may also indicate structural limitations in the model, where calibration parameters compensate for processes that are not explicitly represented.

In the context of *ForEdgeClim*, this interpretation is particularly relevant for parameters such as  $i_m$ , which control the spatial influence of macroclimatic conditions within the forest. As discussed in response to your first major comment (comment 2), the current model version does not explicitly represent wind-driven advection or turbulent transport processes. As a result, parameters such as  $i_m$  may partially compensate for the absence of explicit wind-driven heat exchange.

We therefore agree with the reviewer that both interpretations should be considered. In the revised manuscript, we have expanded the discussion to acknowledge that parameters reaching their bounds may reflect not only restrictive prior ranges but also structural simplifications in the current model formulation. In particular, we now discuss the possibility that parameters controlling the spatial influence of macroclimatic conditions may partially compensate for the absence of explicit wind-driven transport processes.

Section 6.3 Parameter identifiability and equifinality, Lines 827–838:

### **6.3 Parameter identifiability and equifinality**

Beyond the calibrated parameter values, the calibration behaviour provides insight into parameter identifiability within *ForEdgeClim*. For specific seasons or for the full annual calibration, one or both of two parameters converged toward the upper bounds of their prescribed prior ranges, indicating reduced identifiability under particular conditions. In addition to reflecting restrictive prior ranges, such behaviour may also indicate structural limitations in the model formulation. In particular, parameters that control the spatial influence of macroclimatic conditions, such as  $i_m$ , may partially compensate for the absence of explicitly represented processes. As shown in the residual analysis, model–observation discrepancies increase under higher wind speeds, suggesting that wind-driven advection and turbulent mixing are not fully captured. However, the convergence of  $i_m$  towards its upper bound cannot be uniquely attributed to wind-related processes. More generally, it may reflect a compensatory extension of macroclimatic influence into the forest to account for missing or simplified processes affecting heat transport and energy exchange, which may include, but are not limited to, wind-driven mechanisms. These findings indicate that parameter compensation and structural model limitations may jointly contribute to the observed calibration behaviour, consistent with context-dependent equifinality, whereby different parameter combinations can yield similarly good model performance (Beven, 2006; Luo et al., 2009).

### Reviewer 2 Comment 9

The model is run at 1 m resolution but resolution is stated to be configurable. In the introduction of the model, the author claimed that the resolution can be adjusted based on need but no test at alternative resolutions is provided.

#### Response:

We agree that while the model framework allows the voxel resolution to be adjusted, the simulations presented in this study were performed at a spatial resolution of 1 m. This resolution was selected as a compromise between capturing relevant structural heterogeneity in the forest canopy and maintaining computational tractability for the 3D voxel-based simulations.

The statement in the introduction that the resolution can be adjusted refers to the flexibility of the model framework rather than to analyses conducted in this study. We acknowledge that the manuscript did not clearly distinguish between the conceptual flexibility of the modelling framework and the specific configuration used in the presented simulations.

In response to the reviewer's comment, we have clarified that the simulations presented in this study were performed at a 1 m voxel resolution and that the possibility of adjusting the spatial resolution refers to the flexibility of the modelling framework rather than to analyses conducted in this study. We also added a note that evaluating the effects of voxel resolution on model performance represents a potential direction for future work.

Section 2 Model description, Lines 77–87:

## 2 Model description

*ForEdgeClim* is a 3D, process-based microclimate model, implemented as an open-source R package (GitHub: <https://github.com/qforestlab/ForEdgeClim>) and developed to simulate fine-scale temperature gradients along transects from the forest core towards the forest edge. The model operates on a spatially explicit voxel grid with a user-defined spatial resolution, here set to  $1\text{ m} \times 1\text{ m} \times 1\text{ m}$ , in which each voxel represents a discrete three-dimensional volume of forest space. In this study, all simulations were performed at a spatial resolution of 1 m, selected as a compromise between resolving fine-scale structural heterogeneity and maintaining computational tractability. While the voxel resolution is configurable within the model framework, the effects of alternative spatial resolutions on model performance were not evaluated here and remain an important direction for future work. The model simulates microclimate conditions for individual time points based on meteorological input data, allowing the representation of instantaneous or (near) steady-state temperature patterns under specified atmospheric conditions.

Section 6.5 Model limitations and future development roadmap, Lines 893–897 and lines 932–936:

### Key limitations

[...]

While a 1 m resolution was adopted in this study as a compromise between structural detail and computational efficiency, changes in spatial resolution may alter the representation of canopy heterogeneity and thereby influence radiative transfer and heat exchange processes. The sensitivity of model results to voxel resolution was not evaluated in the current study and remains an important source of structural uncertainty.

[...]

#### **Future development roadmap**

[...]

In addition, the choice of voxel resolution is closely linked to the representation of canopy structure. While the current study adopts a 1 m resolution, changes in spatial resolution directly affect how structural heterogeneity is represented within the voxel grid, with potential implications for radiative transfer, heat exchange, and parameter sensitivity. Future work should therefore systematically evaluate the influence of voxel resolution on model behaviour and performance, in order to guide scale-aware application of the model.

#### **Reviewer 2 Comment 10**

Holding  $\omega$ ,  $\beta$ ,  $\beta_0$  constant year-round in a deciduous forest is a strong assumption. Even without leaf-wood separation, allowing these parameters to take seasonally varying values (e.g., two sets: leaf-on and leaf-off) would better represent reality. See also Major Comment 2.

#### **Response:**

We agree that in deciduous forests, canopy optical properties vary substantially between leaf-on and leaf-off periods. In response to this comment, we have extended the model to include seasonally varying optical parameters by introducing separate parameter sets for leaf-on and leaf-off conditions (see Table A5).

This update allows the model to capture first-order seasonal differences in canopy radiative behaviour associated with the presence or absence of foliage. Consistent with the findings reported in our response to your second major comment (comment 3), the impact of this modification on simulated air temperature remains limited, while effects on light availability are more pronounced (Fig. R1).

We refer to our detailed response to your second major comment (comment 3) for further discussion of the implementation and implications of this modification.

#### **Reviewer 2 Comment 11**

Runtime of 20 s to 2 min per hourly timestep is reported, but how this scales with transect length or voxel count is not discussed. From a user side, I am curious to know whether this is feasible on a standard workstation.

#### **Response:**

The runtime reported in the manuscript (approximately 20 seconds to 2 minutes per hourly timestep) corresponds to simulations performed on a standard workstation using the spatial

domain and voxel resolution described in the study. The computational cost primarily scales linearly with the number of voxels in the model domain, as most calculations are performed locally within each voxel or between neighbouring voxels.

As a result, runtime increases approximately with the total number of voxels in the simulation domain, which depends on both the spatial resolution and the domain size. In the present application, simulations were performed at a 1 m voxel resolution over a forest transect represented by a 135 m × 30 m × 38 m voxel grid (resp. edge-to-core length × length perpendicular to the edge × forest height), which remains computationally feasible on a standard workstation.

In response to the reviewer's suggestion, the manuscript was revised to clarify the computational performance of the model and how runtime scales with voxel resolution and domain size. More precisely, we specified that the simulations presented in this study were performed at a 1 m voxel resolution over a 135 m × 30 m × 38 m voxel grid, which remained computationally feasible on a standard workstation.

Section 2.4 Numerical implementation, Lines 361–367:

For the voxel resolution used here (1 m<sup>3</sup>), a single model run for one hourly time point required between 20 seconds and two minutes of computation on a Dell laptop equipped with an Intel® Core™ i7-13800H processor (2.50 GHz) and 32 GB RAM running a 64-bit operating system. These simulations were performed on a voxel grid of 135 m × 30 m × 38 m (edge-to-core length × width × canopy height). The computational cost scales approximately linearly with the total number of voxels in the domain, and thus depends on both spatial resolution and domain size, as most calculations are performed locally within or between neighbouring voxels. For such a run, the energy balance error was constrained to less than 2 W m<sup>-2</sup>, which typically required between 7 and 10 iterations to achieve convergence (see appendix Fig. C1).

### 3 Reviewer 3: Run Zhong

#### 3.1 General comments

##### Reviewer 3 Comment 1

The manuscript introduces *ForEdgeClim* v1.0, a timely and computationally innovative 3D process-based model designed to simulate the complex microclimates of fragmented forest landscapes. The authors should be commended for their ambitious integration of high-resolution Terrestrial Laser Scanning (TLS) data into a voxel-based energy balance framework, which addresses a long-standing limitation in traditional 1D microclimate modeling. The open-source nature of the code and the successful demonstration of lateral thermal gradients provide a valuable foundation for the forest ecology community.

However, while the structural framework is impressive, the physical representation of certain dynamic processes requires further refinement. A primary concern is the current model's reliance on several static assumptions – most notably regarding vegetation phenology, radiative transfer anisotropy, and the absence of advective heat transport. For a model aiming at "high-resolution" 3D simulation, the gap between structural complexity (via TLS) and process simplification remains significant. Major revisions are suggested to either incorporate these dynamic factors or, at a minimum, provide a rigorous discussion of how these limitations constrain the model's applicability across different seasons and environments.

##### Response:

We thank the reviewer for the constructive assessment of our manuscript and for recognising the potential of the *ForEdgeClim* framework for simulating forest microclimates using high-resolution structural information derived from TLS data.

We agree with the reviewer that while the structural representation of the forest canopy is highly detailed, several physical processes are currently represented using simplified formulations. The goal of *ForEdgeClim* v1.0 is to introduce a spatially explicit 3D modelling framework that can resolve microclimate gradients within complex forest structures while maintaining computational tractability. As a result, some processes are currently represented in simplified form or are not yet explicitly included.

In response to the reviewer's comment, we have expanded the discussion of model limitations and future development in Section 6.5 to more clearly describe how several processes could be incorporated in future model versions. In particular, we now discuss the potential integration of wind-driven turbulent transport, improved representations of canopy structure and phenology (including leaf-wood separation), and extensions of the radiative and energy balance formulations.

These revisions aim to more clearly define the scope of *ForEdgeClim* v1.0 and to outline how the current framework can serve as a foundation for progressively incorporating additional physical processes in future model developments. All the improvements are outlined in more detail below, within the specific comments.

## 3.2 Specific comments

### Reviewer 3 Comment 2

Point 1: The Paradox of Structural Simplification:

The decision to omit the Clumping Index and LAD as independent parameters is a critical weakness. While the authors may frame this as a "trade-off" between computational efficiency and data availability, this logic is inherently flawed for a model utilizing TLS data. TLS is precisely the tool meant to resolve fine-scale clustering and structural orientation. By treating voxels as homogeneous turbid media, the model misses the "gap fraction" dynamics essential for edge effects, where lateral light penetration is governed by canopy gaps rather than bulk density. This simplification leads to a systematic underestimation of radiation transmission to the sub-canopy and biases the resulting thermal equilibrium.

### Response:

We agree that canopy clumping and leaf area distribution (LAD) play an important role in determining light penetration and gap fraction dynamics within forest canopies. In the current version of *ForEdgeClim*, canopy structure is represented using a three-dimensional voxel grid derived from TLS data, where each voxel contains a structural density value ( $\rho$ ) that reflects the local abundance of vegetation elements.

This voxel-based representation differs from traditional one-dimensional turbid medium canopy models, as structural heterogeneity and canopy gaps are already represented explicitly at the voxel scale. In other words, the spatial distribution of empty and vegetation-filled voxels derived from TLS data inherently captures much of the gap fraction variability within the canopy structure.

In this context, clumping and LAD can be interpreted as emergent properties of the underlying point cloud density and its spatial configuration, rather than as independent prescribed parameters. As a result, the model implicitly accounts for structural heterogeneity that would otherwise need to be parameterised through clumping indices or LAD profiles in more aggregated canopy representations.

We acknowledge, however, that the current formulation does not explicitly represent LAD or clumping indices as independent structural parameters within voxels. Instead, vegetation within each voxel is treated as a bulk medium with uniform optical properties. As suggested by the reviewer, incorporating more detailed structural descriptors could further improve the physical realism of the radiative transfer calculations. In addition, increasing the spatial resolution of the voxel grid may allow for a more explicit representation of fine-scale canopy heterogeneity and gap fraction dynamics, although this would come at increased computational cost.

Future model developments could therefore incorporate more detailed TLS-derived structural metrics, such as voxel-level leaf-wood separation or leaf area density estimates, which would allow the radiative transfer scheme to better represent within-voxel heterogeneity and canopy clumping effects.

The manuscript was revised to clarify that the voxel-based representation derived from TLS data already captures a substantial portion of canopy structural heterogeneity and gap fraction variability. In addition, the discussion section was expanded to acknowledge that incorporating

more detailed TLS-derived structural metrics (e.g., leaf area density or clumping metrics) could further improve the representation of canopy structure in future model versions.

Section 2 Model description, Lines 88–98:

This voxel-based, 3D formulation allows *ForEdgeClim* to directly integrate detailed 3D information on canopy and understorey structure – derived from terrestrial, mobile, or airborne sensing, or any comparable 3D data source – thereby linking structural heterogeneity to microclimatic variation. Each voxel contains a normalised density value between 0 and 1, which serves as a proxy for vegetation density and governs both radiative transfer and energy exchange. While vegetation within each voxel is treated as a bulk medium with uniform optical properties, structural heterogeneity at the canopy scale, including the presence of canopy gaps, is explicitly represented through the spatial configuration of voxel densities derived from TLS data. As a result, gap fraction variability and aspects of canopy clumping emerge from the three-dimensional arrangement of occupied and empty voxels, rather than being prescribed through explicit clumping indices or leaf area density profiles. The fully 3D formulation enables the simulation of vertical and lateral energy fluxes, capturing the complex interactions that characterise forest edge environments. Details on high-resolution structural data processing and normalisation are provided in Sect. 3, and a detailed description of each model subprocess is presented in the subsequent sections of this paper.

Section 6.5 Model limitations and future model development roadmap, Lines 887–897 and lines 925–936:

### **Key limitations**

[...]

Second, the representation of canopy structure is simplified. Vegetation elements within each voxel are treated as a bulk medium using a structural density ( $\rho$ ), without explicit separation of foliage and woody components. While the voxel-based representation derived from TLS data captures large-scale structural heterogeneity and gap fraction variability, sub-voxel variability (e.g., leaf area density profiles or canopy clumping) is not explicitly resolved. In addition, although seasonal variation in canopy density is partially represented through PAI scaling, optical properties are simplified and only represented at a coarse seasonal level (leaf-on versus leaf-off), which may not fully capture transitional phenological dynamics. In addition, the representation of canopy structure is inherently dependent on the chosen voxel resolution. While a 1 m resolution was adopted in this study as a compromise between structural detail and computational efficiency, changes in spatial resolution may alter the representation of canopy heterogeneity and thereby influence radiative transfer and heat exchange processes. The sensitivity of model results to voxel resolution was not evaluated in the current study and remains an important source of structural uncertainty.

[...]

### **Future development roadmap**

These limitations define a clear roadmap for future model development (Fig. 10).

[...]

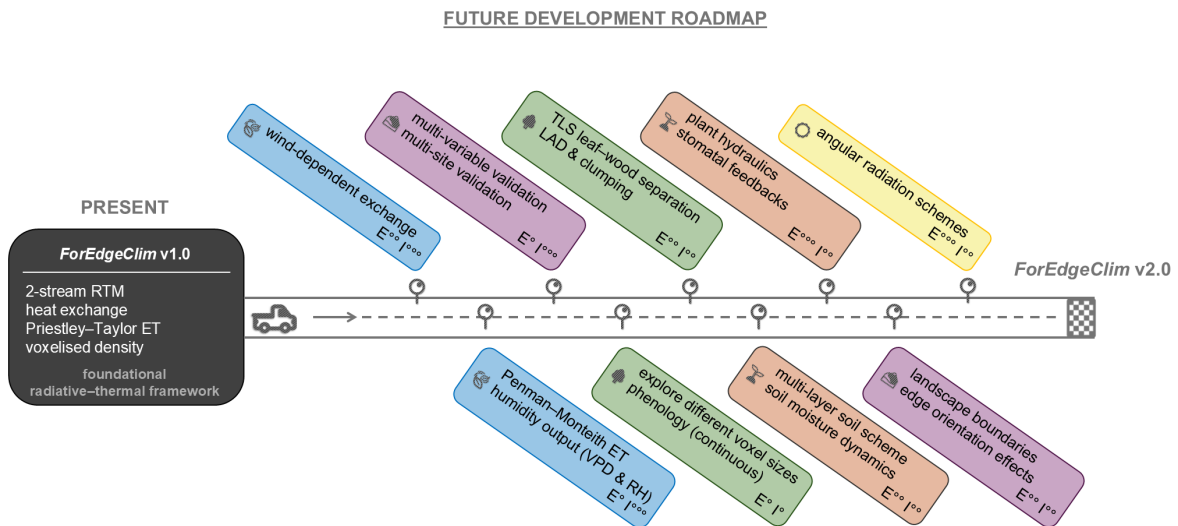


Figure 10: Conceptual development roadmap for the *ForEdgeClim* radiative-thermal core, illustrating the progression from the current model formulation (present) towards a target fully coupled three-dimensional microclimate model. The road visualisation represents a continuous development trajectory along which key model extensions are introduced, including atmospheric coupling (blue), improved boundary conditions and validation (purple), canopy structure refinement (green), soil-plant interactions (brown), and advanced radiation schemes (yellow). For each extension, the expected implementation effort (E) and potential model impact (I) are indicated using a qualitative rating, where the number of symbols (°) reflects relative magnitude (e.g., E° denotes low effort, I°°° denotes high impact).

A second development pathway concerns structural refinement of the canopy representation. This could be implemented by partitioning voxel-level density into leaf and woody components, allowing distinct optical and physiological properties to be assigned within each voxel while preserving the existing spatial discretisation. Incorporating TLS-based leaf-wood separation and voxel-level structural metrics (e.g., leaf area density or clumping indices) would improve the representation of radiative transfer and evapotranspiration processes, similar to approaches used in ecosystem models such as *ED2.2* (Longo et al., 2019) and *DART* (Gastellu-Etchegorry et al., 2004). While seasonal variation in optical properties is already represented through leaf-on and leaf-off parameter sets, further developments could enable a more continuous and mechanistic representation of phenological transitions. In addition, the choice of voxel resolution is closely linked to the representation of canopy structure. While the current study adopts a 1 m resolution, changes in spatial resolution directly affect how structural heterogeneity is represented within the voxel grid, with potential implications for radiative transfer, heat exchange, and parameter sensitivity. Future work should therefore systematically evaluate the influence of voxel resolution on model behaviour and performance, in order to guide scale-aware application of the model.

### Reviewer 3 Comment 3

Point 2: Incorporating Seasonal Phenology into Optical Properties:

For a "process-based" model applied to deciduous forests, the assumption of static leaf optical properties (e.g., constant reflectance in the 400–700 nm range) may limit accuracy during transitional periods. In reality, leaf spectral signatures and Leaf Area Density (LAD) shift significantly from summer greenness to winter senescence. While I recognize that on-site spectral measurements may not always be available, a high-resolution 3D model should ideally account for this temporal resolution. At a minimum, the authors should explicitly discuss this limitation and its potential impact on energy balance during spring and autumn. If empirical leaf-off/leaf-on scaling is not feasible in v1.0, this should be identified as a critical area for future development.

#### Response:

We agree that in deciduous forests, canopy optical properties and leaf area distribution change substantially over the course of the year, particularly during spring leaf emergence and autumn senescence. In the original version of the manuscript, seasonal changes in canopy density were partially represented through monthly scaling of voxel density using plant area index (PAI), while optical parameters ( $\omega$ ,  $\beta$ ,  $\beta_0$ ) were assumed constant throughout the year.

We acknowledge that this simplification does not capture seasonal variation in leaf optical properties or changes in leaf area density associated with phenological transitions, which may affect the representation of radiative transfer and energy balance during transitional periods.

In response to the reviewer's suggestion, we extended the model to include seasonal variation in canopy optical properties by introducing separate parameter sets for leaf-on and leaf-off conditions. The optical parameters ( $\omega$ ,  $\beta$ ,  $\beta_0$ ) now vary between these two states, enabling the model to represent seasonal changes in canopy radiative behaviour. The selection between leaf-on and leaf-off parameter sets is prescribed based on the season of the input data, with leaf-off conditions applied from November to March and leaf-on conditions during the remainder of the year. We note that this update did not lead to observable changes in the results presented in this study. Although the model was applied across four seasonal datasets, only the winter period (January 2025) is affected by this modification, as the other seasons were already represented using leaf-on conditions. Even for the winter dataset, the impact of the updated optical parameters remains very limited. This is consistent with the sensitivity analysis, which shows that shortwave radiative transfer parameters have a relatively small influence on simulated air temperature. Consequently, no visible differences in air temperature patterns were observed following this modification. We note, however, that changes in canopy optical properties do have a stronger influence on light availability and interception, as illustrated in Fig. R1 (included in this response). We further note that small numerical differences between model runs can arise due to stochastic components in the sensitivity analysis and optimisation procedures. These differences are of similar magnitude to the effect of the present modification and do not affect the interpretation of the results.

More advanced developments could further refine this approach by explicitly representing foliage and woody components within the voxel grid using TLS-based structural information, allowing distinct optical properties to be assigned to each component and enabling a more continuous representation of phenological transitions.

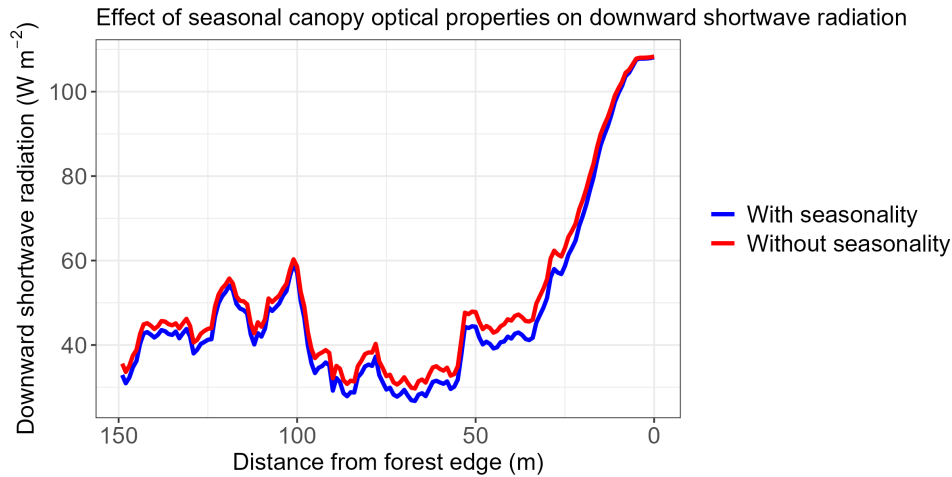


Figure R1: Effect of seasonal canopy optical properties (leaf-on versus leaf-off parameterisation) on downward shortwave radiation for a winter case (15 January 2025, 12:00 UTC). The figure shows the mean downward shortwave radiation averaged over all north–south slices, plotted along the east–west transect line.

The manuscript has been revised accordingly to describe the implementation of seasonally varying optical parameters and to reflect this improvement in the model formulation. Here we refer to our answer to your previous comment (comment 2) regarding our updates in Section 6.5 Model limitations and future development roadmap. In addition we have also updated the appendix Table A5 (see below).

Appendix Table A5:

**Table A5.** Assumptions and limitations of the two-stream RTM in *ForEdgeClim*.

- ◇ Voxel density does not distinguish between leaf and wood, or between tree species.
- ◇ No spectral variation within both the shortwave and longwave band.
- ◇ Optical properties are spatially uniform and represented using two seasonal parameter sets (leaf-on and leaf-off), without resolving leaf and woody components within voxels.
- ◇ The longwave RTM assumes a constant emissivity across all forest surfaces.
- ◇ The canopy is assumed to have a spherical leaf angle distribution.

#### Reviewer 3 Comment 4

Point 3: Physical Consistency of the 3D Radiative Transfer Scheme:

The application of the two-stream approximation in a 3D voxelized framework at forest edges introduces a fundamental physical inconsistency. The classical two-stream theory (as presented in Eqs. 2-5) was originally derived for 1D horizontally homogeneous media, assuming an isotropic diffuse radiation field. However, at a forest edge, the radiative environment is characterized by extreme anisotropy due to the lateral influx of direct and diffuse solar radiation.

In Section 2.1.1 and Figure 1, the model handles lateral fluxes ( $\phi_x$  and  $\phi_y$ ) by extending the vertical two-stream equations. While this approach simplifies the computation, it may not fully capture the directional nature of photon interception at the edge, which is governed by the specific geometry of canopy gaps and the solar position. Although the authors describe this as a "3D process-based" model, the current use of two-stream approximations for lateral fluxes effectively treats the complex 3D light field as a series of coupled 1D problems. This simplification could potentially limit the model's ability to accurately resolve the extinction coefficient and the resulting thermal gradients in highly heterogeneous transition zones.

Given that the model already operates on a 3D voxel grid, more advanced schemes such as the Discrete Ordinates (DO) method or Spherical Harmonics expansion would be more robust for discretizing the angular domain and capturing the non-isotropic nature of the edge radiation field. At a minimum, I recommend that the authors provide a more detailed justification or a sensitivity analysis to demonstrate the validity of the isotropic assumption, particularly at the immediate forest edge where the thermal gradient is most pronounced.

#### Response:

We agree that the classical two-stream approximation was originally developed for one-dimensional, horizontally homogeneous canopies and assumes an isotropic diffuse radiation field. In the current model formulation, the two-stream approach is extended to a three-dimensional voxel grid by solving radiative transfer separately along vertical and lateral directions. As correctly noted by the reviewer, this approach effectively represents the three-dimensional radiation field as a set of coupled one-dimensional radiative transfer problems.

This formulation represents a deliberate trade-off between physical realism and computational efficiency. The aim of *ForEdgeClim* is not to fully resolve the angular distribution of the radiation field within a complex canopy structure, but rather to capture the dominant radiative gradients arising from vertical attenuation through the canopy and lateral radiative penetration from forest edges. Within this context, the directional two-stream approach provides a computationally efficient approximation that can be applied across large voxel domains derived from TLS data.

Importantly, the model does not assume a fully isotropic radiation field, as it explicitly distinguishes between vertical and lateral fluxes and accounts for solar angle effects. However, the angular distribution of radiation is represented in a simplified manner using a limited number of discrete directions. As such, the approach can be considered partially anisotropic, while not resolving the full directional complexity of the radiative field.

In addition, diffuse radiation fields within forest canopies are often close to isotropic due to multiple scattering between leaves and branches, particularly in dense temperate forests (Bonan, 2019). Under such conditions, two-stream approximations have been shown to reproduce bulk radiative attenuation reasonably well, even when canopy structure exhibits spatial heterogeneity. The present formulation therefore aims to capture the dominant attenuation processes rather than the full angular distribution of photons.

We agree that more advanced radiative transfer approaches – such as discrete ordinates methods, spherical harmonics expansions, or Monte Carlo ray tracing – could more explicitly represent anisotropic radiation fields within heterogeneous canopy structures. However, these methods typically come with substantially higher computational costs, which would limit the feasibility of applying the model at the spatial scales and resolutions considered in this study.

In response to the reviewer’s comment, the manuscript was revised to clarify the conceptual interpretation of the radiative transfer scheme used in the model. In particular, we now explicitly state that the current approach represents the three-dimensional radiation field using directional two-stream approximations along vertical and lateral directions. The discussion section was also expanded, including a future roadmap figure, to acknowledge that more advanced radiative transfer schemes could be explored in future model developments.

Section 2.2.1 Radiative transfer model, Lines 232–241:

The shortwave RTM is implemented as a one-dimensional column model. To obtain a two-dimensional radiative field, it is applied sequentially to each vertical column (fixed  $x$  and  $y$ ) and each horizontal row (fixed  $y$  and  $z$ ) in the 3D voxel grid. Direct-beam solar radiation is partitioned between the vertical and lateral directions according to the solar elevation angle, whereas diffuse radiation is assumed to be isotropic, such that vertically and laterally incident diffuse fluxes are equal.

This formulation represents the three-dimensional radiation field as a set of coupled one-dimensional radiative transfer problems. While this introduces a simplified representation of the angular distribution of radiation, it enables the model to capture the dominant radiative gradients associated with vertical attenuation and lateral radiation penetration at forest edges in a computationally efficient manner. As such, the radiative transfer scheme is directionally resolved but does not explicitly discretise the full angular domain of the radiation field. Anisotropy is therefore only partially represented through the separation of vertical and lateral fluxes and the dependence of direct radiation on solar elevation angle.

Section 6.5 Model limitations and future development roadmap, Lines 950–953:

#### **Future development roadmap**

These limitations define a clear roadmap for future model development (Fig. 10).

[ . . . ]

Finally, advances in radiative transfer modelling could be explored within the current framework by replacing or complementing the two-stream approximation with more detailed angular radiation schemes, such as discrete ordinates methods (Stamnes et al., 1988), spherical harmonics expansions (Modest and Lei, 2012), or Monte Carlo ray tracing approaches (Disney et al., 2000), where computationally feasible.

### 3.3 Summary recommendation

#### Reviewer 3 Comment 5

The model shows great promise, but the transition from a "static structural model" to a "dynamic process model" requires a more rigorous treatment of vegetation phenology and fluid dynamics.

#### Response:

We thank the reviewer for this insightful summary and for highlighting the distinction between structural complexity and process representation in the current model formulation.

We agree that, while *ForEdgeClim* v1.0 introduces a high-resolution three-dimensional representation of forest structure based on TLS data, several dynamic processes are currently represented in a simplified manner or are not yet explicitly resolved. In particular, vegetation phenology is represented using discrete seasonal parameter sets (leaf-on and leaf-off), and wind-driven advective heat transport is not explicitly included in the present model version. As such, the current model should be viewed as an intermediate step in the transition from a structurally detailed representation towards a more fully dynamic process-based framework.

As outlined in our responses to the specific comments, we have revised the manuscript to more clearly acknowledge these limitations and their implications for model applicability across seasons and environmental conditions. We have also expanded Section 6.5 to provide a more structured roadmap for future model development, including (i) a more mechanistic representation of phenological dynamics, (ii) improved treatment of canopy structural properties (e.g., leaf-wood separation and leaf area density), and (iii) the incorporation of atmospheric coupling processes such as wind-driven turbulence and advective heat transport. In addition, we revised the model description (Section 2), the radiative transfer formulation (Section 2.2.1), and the treatment of seasonal parameterisation (Appendix Table A5) to more clearly describe the current level of process representation and its limitations. The fully revised Section 6.5 is provided in our response to reviewer 2, comment 6.

We emphasise that the primary objective of *ForEdgeClim* v1.0 is to establish a spatially explicit 3D modelling framework that links high-resolution canopy structure to microclimate gradients in a computationally tractable way. Within this scope, the current model captures the dominant radiative and thermal processes controlling microclimate patterns at forest edges, while providing a flexible foundation for the progressive integration of additional dynamic processes in future model versions.

We have revised the manuscript accordingly to more clearly define this scope and to ensure that the current model is presented as a first step towards a fully coupled three-dimensional microclimate modelling framework.

## 4 Reviewer 4: Vivienne Groner

### 4.1 General comments

#### Reviewer 4 Comment 1

This manuscript presents a new model for a 3D process-based microclimate model that incorporates both vertical and lateral energy fluxes to simulate forest microclimates. The authors provide a detailed description of the model structure, governing equations, and parameterization, together with a calibration procedure and a demonstration case study along a core-to-edge transect in a temperate forest in Belgium. The aim of the model is to provide a tool to better study microhabitats in forest edge-to-core transition zones.

The paper addresses a very timely and relevant scientific modelling question within the scope of GMD, namely the role of microclimate in governing ecological processes, and presents a novel modelling tool suitable for addressing important research questions in this area and in the broader scope of EGU. The work represents a substantial advancement in the field of microclimate modelling, as it brings in a whole new dimension/set of processes, and opens up potential for new research in ecology and climate science.

The methods and assumptions appear valid and are clearly outlined. The manuscript provides a clear and very detailed description of the governing equations, parameterizations, calibration and validation procedures, and overall model structure, illustrated by a schematic figure. In addition, the extensive supplementary material and the reference to the code repository on GitHub further support reproducibility and transparency. The code itself is well written and documented, meeting a high code quality standard. This level of detail should allow other researchers to reproduce and build upon the work. The assumptions and limitations of the approach are discussed in detail and are generally supported by previously published studies. The presented results are sufficient to support the interpretations and conclusions presented in the manuscript. The figures are generally well chosen and support the main messages of the paper.

The overall presentation is well structured and clear, and I enjoyed reading the manuscript. The title clearly reflects the contents of the paper, and the abstract provides a concise and complete summary of the study. The language is generally fluent and precise, although in a few places sentences appear a bit unclear or inconsistent, potentially due to the use of LLM for tidying the final version. Mathematical formulation, symbols, abbreviations, and units are generally defined and used appropriately. The number and quality of references are appropriate and the cited literature is recent. The supplementary material is extensive and of good quality, and appropriately complements the methods presented in the main text. I recommend minor revisions.

#### Response:

We thank the reviewer for the positive and constructive assessment of our manuscript and for recognising the potential of the *ForEdgeClim* framework for studying forest microclimates in spatially heterogeneous landscapes.

We appreciate the reviewer's comments regarding the clarity of the manuscript and the transparency of the model description, code availability, and supplementary material. In response to the reviewer's suggestion, we carefully reviewed the manuscript to improve clarity and consistency

in several sentences and formulations.

The suggested improvements are outlined in more detail below, within the specific comments.

## 4.2 Specific comments

### Reviewer 4 Comment 2

Time step / temporal representation:

It was not entirely clear to me what temporal resolution the model operates at. From the introduction, my understanding is that the model assumes an equilibrium state; however, the manuscript also mentions a time interval of one hour. It would be helpful if the authors could clarify how time is represented in the model. Following that, I would be interested how would the model perform over multiple time steps potentially integrated with other ecological models, like a forest gap model.

### Response:

In the current model formulation, *ForEdgeClim* calculates a steady-state energy balance for each simulated time point. This means that for a given set of environmental forcing variables (e.g., macroclimate temperature, radiation, and soil temperature), the model iteratively solves the energy balance until equilibrium conditions are reached within the voxel grid.

In the present study, the model was applied using hourly meteorological forcing data. For each hourly time step, the model computes the equilibrium microclimate conditions corresponding to that specific set of environmental inputs. The model therefore does not simulate temporal heat storage or dynamic transitions between time steps, but instead treats each time step independently.

As noted by the reviewer, this approach allows the model to be applied sequentially over time using time series of meteorological forcing. In principle, the resulting microclimate predictions could therefore be integrated with ecological models (e.g., forest gap models) that operate at hourly or daily time scales.

In response to the reviewer's comment, the manuscript was revised to clarify that *ForEdgeClim* calculates steady-state microclimate conditions for each simulated hourly time point. We also clarified that the model can be applied sequentially using hourly meteorological forcing data, although temporal heat storage is not explicitly simulated.

Section 2 Model description, Lines 115–126:

A schematic overview of the model workflow is presented in Fig. 1. Convergence is pursued for the forest surface temperature, while air and soil surface temperature (K) are updated diagnostically. The assumption of steady-state conditions is applied at the voxel scale, where local canopy and ground surfaces are assumed to reach thermal equilibrium much faster than the one-hour interval used in the simulations, allowing transient heat storage to be neglected. In the current model formulation, the energy balance is therefore solved independently for each simulated time point. For a given set of environmental forcing variables (e.g., macroclimate temperature, radiation, and soil temperature), the model iteratively converges to equilibrium conditions within the

voxel grid. In this study, the model was applied using hourly meteorological forcing data, such that each time step represents a separate equilibrium solution. As a result, temporal heat storage and dynamic transitions between time steps are not explicitly simulated, and the model does not retain memory of previous states. Nevertheless, the model can be applied sequentially using time series of meteorological forcing data, allowing the reconstruction of temporally evolving microclimate patterns as a sequence of quasi-steady-state solutions. This formulation also enables coupling with ecological or vegetation models operating at hourly or daily time scales.

#### Reviewer 4 Comment 3

Temperature only:

Right now, the model only outputs temperature, which is common in this field. But since microclimates usually involve more than just temperature, it could be interesting to extend it to other variables too, like relative humidity or wind speed. Could you comment on the potential for the model to do so?

#### Response:

We agree that microclimates are characterised by multiple atmospheric variables, including humidity and wind, which can play an important role in ecological processes and organismal responses. In the current version of *ForEdgeClim*, the model focuses on temperature as the primary output variable, as temperature gradients are among the most widely studied and ecologically relevant aspects of forest microclimates, and because temperature is the variable for which the most extensive and spatially resolved site measurements are available for model calibration and evaluation.

We acknowledge that humidity and wind are not explicitly represented in the current model formulation. Evapotranspiration is calculated using a Priestley–Taylor approach, which assumes radiation-driven latent heat fluxes and does not explicitly account for atmospheric demand. Similarly, heat exchange is represented using bulk transfer coefficients ( $g_m$ ,  $g_s$ , and  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ , and  $i_f$ ), which are treated as constant parameters and therefore do not vary with wind speed or atmospheric stability. As a result, wind-driven heat and mass transfer processes are not explicitly resolved.

Nevertheless, the model framework is designed to allow the incorporation of additional microclimatic variables in future developments. In particular, extending the evapotranspiration formulation to a Penman–Monteith approach would enable the explicit representation of humidity-related variables such as vapour pressure deficit (VPD) and relative humidity (RH). Likewise, wind dependency could be introduced by linking the convection coefficients and distances of influence to wind speed and canopy structural properties, allowing a more mechanistic representation of turbulent exchange processes within the voxel grid.

In response to the reviewer’s suggestion, we have expanded the discussion of potential future model developments in Section 6.5 to highlight the incorporation of additional microclimatic variables such as humidity and wind. This section now also includes a conceptual roadmap figure outlining the main development pathways of the model.

Section 6.5 Model limitations and future development roadmap, Lines 877–886 and lines

### Key limitations

Several limitations arise from the simplified representation of physical processes in the current model version.

First, canopy–atmosphere exchange processes are only partially represented. Wind-driven turbulence, advection, and momentum transfer are not explicitly simulated, although these processes play a key role in shaping forest microclimates, particularly at forest edges (Chen et al., 1995; De Frenne et al., 2021). Sensible heat exchange is parameterised using a bulk heat transfer coefficient, and evapotranspiration is represented using a Priestley–Taylor formulation, which assumes radiation-driven latent heat fluxes and neglects explicit aerodynamic control. While this assumption is often reasonable for forest interior conditions, it may be less appropriate near forest edges where horizontal advection of heat and moisture can modify evaporative demand. This limitation is also reflected in the residual analysis, which indicates that model–observation discrepancies increase under higher wind speeds, particularly in structurally open areas where atmospheric coupling is enhanced.

[ . . . ]

### Future development roadmap

These limitations define a clear roadmap for future model development (Fig. 10).

A first priority is to improve the representation of canopy–atmosphere exchange by incorporating wind-dependent aerodynamic processes. This can be achieved within the existing voxel-based framework by linking the current bulk heat transfer coefficients ( $g_m$ ,  $g_s$ ,  $g_f$ ) and distances of influence ( $i_m$ ,  $i_s$ ,  $i_f$ ) to wind speed and canopy structural properties (Maurer et al., 2013; Kimura et al., 2020; Flayyih Al-Rikabi et al., 2024). Such an extension would allow turbulent mixing and advective heat transport to be represented more explicitly, while retaining the current parameterisation structure. Extending the evapotranspiration formulation to a Penman–Monteith framework would further enable explicit representation of canopy resistance and atmospheric demand, and facilitate the inclusion of humidity-related state variables such as vapour pressure deficit and relative humidity.

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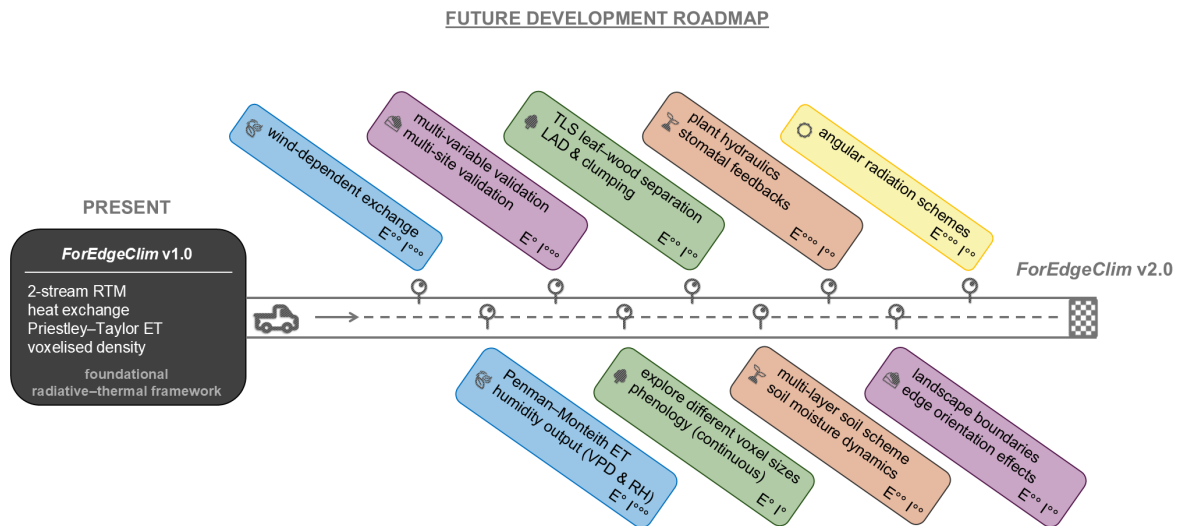


Figure 10: Conceptual development roadmap for the *ForEdgeClim* radiative-thermal core, illustrating the progression from the current model formulation (present) towards a target fully coupled three-dimensional microclimate model. The road visualisation represents a continuous development trajectory along which key model extensions are introduced, including atmospheric coupling (blue), improved boundary conditions and validation (purple), canopy structure refinement (green), soil-plant interactions (brown), and advanced radiation schemes (yellow). For each extension, the expected implementation effort (E) and potential model impact (I) are indicated using a qualitative rating, where the number of symbols (°) reflects relative magnitude (e.g., E° denotes low effort, I°°° denotes high impact).

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