Reviewer 2

Reviewers' comments are in black font, our responses are in blue and green is for new and revised text; to assist with navigation, we use codes, such as R2C1 for Reviewer 2 Comment 1.

General comments:

In this manuscript, the authors describe the one-dimensional numerical model of tree hydrodynamics SPAC-3Hpy with explicit Richards-like solutions of flow in soil, root, and stem domains. It is proposed to validate it against analytical solutions of water flow in porous media, and against tree transpiration data. The scope is of great interest to the readership of Geoscientific Model Development. Overall, the study is interesting, well explained and provides clear illustrations.

We thank Dr Couvreur for his overall positive evaluation of our work.

My main concerns regarding publication in GMD are (i) the need for clarifications and small improvements that would facilitate the interpretation of the manuscript, (ii) the validation against transpiration data that I think does not meet the quality of the rest of the manuscript, and (iii) the lack of a proper contextualization of the model relative to the galaxy of existing tree hydrodynamics models that could be developed in a discussion section.

We have addressed the 3 points raised by the Reviewer in the answers to the specific comments below. In relation to the discussion section, we decided to add a section between the Introduction and the Model description to provide the context requested by both Reviewers.

To provide a clearer contextualization of the model, we decided to change the name of the model to FETCH3, and this is used in this document. Although the acronym no longer reflects the nature of the model and numerical scheme used to solve the equations, it easily relates to the developments that FETCH has had over the years.

Specific comments:

R2C1 (L11): The term "hydroactive" xylem is a bit odd as the process of water flow in xylem is passive as described in the introduction of the paper. Also, throughout the paper the authors seem to use the term "xylem" when referring to the stem (e.g. also at L84). This is confusing as there is xylem in roots and leaves too. I would suggest to revise the wording.

Thank you for the suggestion. We removed the term "hydroactive" xylem and introduced the terms "stem xylem" and "root xylem" to improve the reading.

R2C2, L12: I am enthused that the authors made their model open access. It also seems that the code is open source, which is even better I believe. If that is correct, why not making it explicit in the text?

Thank you for your comment. We added in the Introduction:

"The aim of this study is to present FETCH3, an open source and open access tree hydrodynamic model for the simulation of the temporal and vertical dynamics of water storage and fluxes from the soil to the atmosphere, accounting for the vegetation response to environmental conditions and soil water availability."

R2C3, L21-22: I think the sentence needs to be completed. Upward flow of water in 20 m trees would also be possible without the tension-cohesion mechanism, using an osmotic pressure difference of 0.2 MPa between soil and xylem. The tension-cohesion theory explains that this upward flow is possible without an osmotic driving force, along a continuum of liquid water under tension.

We added in the referred lines: "Most models that explicitly resolve the movement of water within the plant system rely on the cohesion-tension theory, which explains how water can be transferred upward from the soil to the atmosphere across a tree height of several meters, in the absence of osmotic pressure differences (**Couvreur et al., 2018**)."

R2C4, L40-42: Root water uptake compensation and hydraulic redistribution can also be modelled with "electric circuit" models that do not account for the plant water capacitance (see e.g. Meunier et al. (2017); Kennedy et al. (2019)). A major progress with the capacitance is that water fluxes along the stem do not have to be vertically equal simultaneously (e.g. as observed in Sperling et al. (2012) in palm) and that the integral of root water uptake does not have to match the integral of transpiration at a given time due to variations in stem water storage.

Thank you for your comment. We have added a new section between the Introduction and the Model description to provide a more detail review the existing literature on modelling water fluxes across the soil-plant-atmosphere continuum.

R2C5, L63-64: Similarities with FETCH and FETCH2 are mentioned but differences are unclear and should be clearly explained. A discussion section could as well discuss the specific interest of SPAC-H3py relative to the broader diversity of tree hydrodynamics models.

The differences between the present model, FETCH3, and FETCH2 are summarized in section 2.1 as:

"FETCH3 builds upon FETCH2 (Mirfenderesgi et al., 2016, 2018), which is based on its precursor, the finite element tree crown hydrodynamics (FETCH) model (Bohrer et al., 2005). FETCH simulates water flow along a tree's stem and branches accounting for the branch structure in three dimensions. Simulating the three-dimensional tree crown structure is computational demanding and can solely be applied to a single tree. As a result, FETCH2 was developed to offer a more mechanistic approach that could be scaled to entire ecosystems. To achieve this, FETCH2 simplifies branches along the vertical direction, leading to a 1D model; the equations in FETCH2 are solved using a finite difference scheme (Mirfenderesgi et al., 2016).

Similarly to FETCH and FETCH2, FETCH3 assumes that the water movement in the xylem resembles flow in porous media; as in FETCH2, a macroscopic approach is used to simulate the water fluxes across the soil, roots, and stems with the fluxes being described in one dimension along the vertical direction (Fig. 1). As a development from FETCH2, FETCH3 presents a clearer link between the three different components of the system (i.e., soil, roots and stem), based on the conservation of water in each of the components, as derived in the Supplementary Material. The links between the soil, roots, and stem xylem are clearer in FETCH3, thus providing a more precise coupling of the 3 components of the system. As a result, when combined, the quantities in the equations for the roots and stem are scaled to a reference ground area, consistently with the Richardson-Richards equation for the soil. This guarantees the conservation of mass as water flows from one component to the other. The system of equations in FETCH3 is also solved differently from FETCH2. As described in detail in the Supplementary Material, the equations in FETCH3 are discretised using the method by Celia et al. (1990) generating a system of algebraic equations combined into a single matrix, that is solved at the same time to guarantee the conservation of mass across the whole system comprising soil, roots and stem."

Additionally, we have included in the manuscript a section to discuss the literature on plant hydraulic modelling, and the differences between the modelling approaches. This new section will clarify the pros and cons of each approach.

R2C6, Figure 1: It is good that variables appear in figure 1, so that connections to the equations can be done. However, several of these variables have not been defined at this point, which complicates the interpretation of the figure. There is room for it in the caption, or in the main text already.

The caption of Figure 1 has been modified as:

"Representation of the coupling process between soil, root xylem, and stem xylem applied in the model, where A_s represents a reference ground area, dz an infinitesimal depth over an area (m), z the vertical coordinate (m), V volume of soil (m^3), ρ the density of water (kg m^{-3}), F_{in} (kg s^{-1}) the water fluxes entering and F_{out} (kg s^{-1}) exiting the volume, A_r/A_s (m^2_{root} m^{-2}_{ground}) the root xylem cross area index, A_x/A_s (m^2_{xylem} m^{-2}_{ground}) the stem xylem cross area index, S (s^{-1}) the rate at which water is extracted from the soil and enter the root xylem, and S_x (s^{-1}) the rate of water leaving the stem xylem."

R2C7, L70-72: At this point it is not clear if radial resistances between the bulk soil, root surface and root xylem are considered. It is particularly important to specify it in the overview as they are frequently viewed as the largest resistances in series of the soil plant hydraulic continuum.

FETCH3 considers the radial resistances (which includes a soil moisture stress function), lateral surface area of the roots and root mass distribution when computing the root water uptake. We have added at line 71 of the overview section (2.1):

"Water fluxes within roots are likewise modelled with a Richardson-Richards type equation with the same term (of the opposite sign) representing water exchange between roots and soil. Soil and roots are coupled through this term, such that a sink of water in the soil is a source of water in the roots, and vice versa. The transfer of water between the soil and the roots is modulated by a conductance, representing the radial resistance between the bulk soil, roots surface, and root xylem, and a stress function, accounting for the reduction of the root water uptake associated with different soil moisture conditions possibly leading to water and oxygen stress."

R2C8, L99: I realize it is implicit, but probably worth specifying that the "soil capacitance" is the "soil water capacitance". The same goes for the root and stem water capacitances.

We have changed the terms throughout the manuscript as suggested.

R2C9, L99: Going through the equations I frequently wondered if parameters were constants or could vary in space. For instance, stem cross-sectional area, saturated hydraulic conductivity (here Km I believe) and sensitivity to cavitation (that I guess relate to the water capacitance parameter) vary along tree stems with substantial consequences on the nonlinear vertical water potential profile (Couvreur et al., 2018). It would be worth discussing briefly if such vertical variations of hydraulic parameters can be accounted for in SPAC-3Hpy.

We thank the Reviewer for the suggestion. We have added in the governing equations section (2.1), starting at line 62:

"In its 1D domain, FETCH3 allows for the vertical variation of the soil, root xylem, and stem xylem hydraulic parameters. As a result, the hydraulic conductivities, capacitances, root and stem xylem cross section areas, for example, are able to vary along the tree."

R2C10, L110: I found it confusing that "Sx" does not have the same units as "S" (also in equation 6). The same goes for "Aind" whose symbol suggests area units like "Ax", "As" and "Ar". How about explicitly writing "Ar/As" instead of "Aind"?

We agree with this comment, and have rewritten Equation (3), which now states "S_x" with the same units as the term "S" (s^{-1}). We have also modified the root lateral surface area index from "A_{ind}" to "A_{lr}/A_x ", as suggested. We have modified these terms throughout the manuscript.

Equation 3:

$$C_x \frac{\partial \Phi_x}{\partial t} = \frac{d}{d\Phi_x}\left(\frac{\theta_x A_x}{A_s}\right)\frac{\partial \Phi_x}{\partial t} = \frac{\partial}{\partial z}\left[K_x \frac{A_x}{A_s}\left(\frac{\partial \Phi_x}{\delta z} + \rho g\right)\right] - S_x \frac{A_x}{A_s}$$

Equation 5:

$$S_x \frac{A_x}{A_s} = T\, l(z)$$

R2C11, L122: The use of the subscript (z) for parameters like "r" but not variables like "theta" is a bit confusing. Why not using the subscript (z) for all variables and parameters that vary in space or mention it in a table? The same could be done for those varying in time.

Thank you for this point. We have adjusted Equation (4) and specified the dependence of the variables on space and time in the root water uptake formulation.

Equation 4 now reads:

$$S(z,t) = k_{s,rad} f\big(\theta_s(z,t)\big).\frac{A_{ls}\,(z)}{A_s(z)}.\frac{r(z)}{\int_{z_{r_i}}^{z_{r_j}} r(z)\,dz}.\left(\Phi_s(z,t) - \Phi_r(z,t)\right)$$

R2C12, L122: As it is presented, it is hard to understand why a vertical profile of relative root surface areas multiplies a normalized vertical profile of root mass in equation 4. Both seem to do the same job, don't they? In the discussion section, it would be interesting to discuss this formulation of the radial water flux in the broader context of existing models (e.g. De Jong Van Lier et al. (2008)).

The lateral root surface area index represents the lateral surface area of roots contained in a portion of reference soil area, whereas the root mass distribution represents the percentage of roots from the total root mass (not only accounting the for lateral roots) contained in the same soil reference area. The combination of these two terms in the root water uptake formulation (Eq. 4) scales the model to a more representative coupling of the roots with the soil. To clarify and better explain what this means, we added in section 2.2.1:

"A_{ls}/A_s ($m^2_{root}\ m^{-2}_{ground}$) is an index defining the lateral root surface area per unit of ground, representing the root surface area taking up water from the soil. The vertical profile of root mass distribution represents the percentage of roots contained in different soil layer. The product of these two terms provide the portion of roots contributing to the exchange of water between soil and roots; this changes with depth depending on how the roots are vertically distributed."

R2C13, L129: It is unclear if "T" is normalized by the soil, stem, or leaf surface area. Please clarify it when first introducing the variable.

We have added further clarification in the sentence, which now reads:

"(...) where T (m/s) is the transpiration rate defined per unit of ground area (...)"

R2C14, Figure 6: While I found the comparison with the analytical solution convincing, I am a bit more sceptical about the validation against transpiration rate data. To argue on the need for the new features of SPAC-3Hpy using a validation, I feel it would be relevant to show that the increased complexity and number of parameters is compensated by a substantial increase in the accuracy of the model predictions, possibly justified by the result of an Akaike test. Here the validation rather looks like an example run that fits reasonably well observed transpiration rates. However, with so many parameters involved, one could hardly imagine a poor fit of the transpiration data. This validation attempt that I feel is a bit oversold could be sent to appendices and replaced by a simple discussion contextualising the diversity of tree hydrodynamics models revolving around SPAC-3Hpy and explaining why we need this model, and which gap it will fill.

The case study is presented not as a validation test for FETCH3, but to show the ability of the model to reasonably reproduce experimental observations. The use of the dataset in Verma et al. (2014) is convenient because the observed sapflux rates were modelled with a similar set of equations as FETCH3, thereby not requiring a full calibration of the parameters. The case study shows that, with the same parameters, FETCH3 provides results similar to Verma et al. (2014), who used a finite difference scheme to solve the equations. The case study also serves to highlight the differences in the results that are obtained when including the storage capacity of the stem and a leaf area density distributing the transpiration along part of the stem.

For these reasons, that are better explained in the text, we prefer to keep the case study in the text. The additional section between the Introduction and the Model description will provide the context for the development of FETCH3, as suggested.

R2C15, Figure 6: It seems like there is a problem with inconsistent temporal scales in the top and bottom parts of figure 6. I realize that in a model with stem water capacitance, transpiration and water uptake may happen at slightly different times, but morning transpiration should come slightly before root water uptake, not the opposite. This issue is visible in the first peak. In the last peak, the temporal shift is in the opposite direction, possibly a bit off too. Please could you check the time scales?

We have fixed Figure 6, and it now presents the correct horizontal axis. The figure got shifted when being converted to a higher resolution.

Best of luck with the next steps.

Valentin

References:

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