GEOS518 Term Project
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Understanding CLM5: Plant Hydraulics

1. Introduction

Vegetation stress is becoming increasingly common due to climate change (Ficklin & Novick, 2017; McDowell et al., 2015). In particular, changes in soil moisture and vapor pressure deficits from global warming can lead to higher vegetation mortality. Improving our understanding of how the severity, frequency, and effects of climate change relate to vegetation stress and mortality is vital to understanding how to best manage and conserve ecosystems.

Models such as the Community Land Model (CLM) aim to encapsulate a variety of land and atmospheric processes to better understand different aspects of earth processes (CLM5.0 Technical Description). In doing so, we can gain a better understanding of what processes to target in restoration/conservation efforts. The CLM is one part of the Community Earth System Model (CESM): a large model that investigates global processes from the atmosphere to ocean and beyond. CESM (including CLM) was developed by NSF NCAR and serves as a holistic way to understand earth system processes currently and in the future.

In this paper, I focus primarily on CLM version 5, which introduces physics-based plant hydraulics to the model (Kennedy et al., 2019). This addition to CLM improves vegetation feedback and finds vegetation water potential, which is not calculated in any other earth system model. In doing so, photosynthesis calculations are more sensitive to vapor pressure deficits which directly impact our ability to understand the effects of vapor pressure deficits on vegetation.

In this paper, I aim to gain an understanding of how plant hydraulics are employed in CLM5. I will describe the different processes represented in this model and describe a numerical experiment that this model can perform.

2. Model Description

The overall model is structured following the flow of a plant (CLM5.0 Technical Description). There are three main sections of the model representing plant hydraulics: soil-to-root, root-to-stem, and stem-to-leaf. Water supply and water demand are also important pieces of the model that dictate plant hydraulics and the output of the model. Below, I outline the several of the key processes involved in this model and how they are calculated.

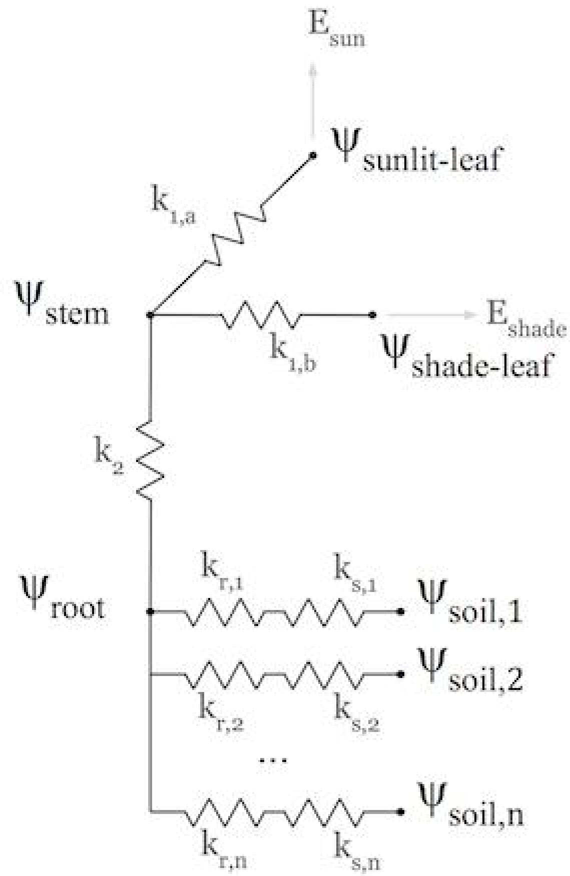

Figure 1. A conceptual figure of the structure of the model (Kennedy et al., 2019).

CLM5 has two configurations: PHS and SMS. PHS (Plant Hydraulic Stress) is the default configuration and introduces a new formula for deriving the water stress factor using leaf water potential. The SMS (Soil Moisture Stress) configuration, found as the default in CLM4.5, relies on soil moisture to understand other surface fluxes such as photosynthesis and transpiration. My analysis will focus on understanding the underlying processes of PHS in CLM5.

Both configurations of the model (CLM5 and CLM4.5) calculate stomatal conductance and photosynthesis using the same process. To calculate stomatal conductance, the Medlyn stomatal conductance model is used. This model combines an empirical approach with carbon-water optimization to calculate stomatal conductance and water stress, which can be converted to leaf water potential. To calculate stomatal conductance (gs), equation 1 is used. It incorporates photosynthesis (An), VPD (vapor pressure deficit) (D), and the concentration of CO2 at the leaf's surface (Ca). Additionally, two parameters must be defined: the minimum stomatal conductance (g0) and the marginal water cost related to carbon assimilation optimization (g1).

$$g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{D}}\right)\frac{A_n}{C_a}.$$

eq. 1

The process of deriving photosynthesis estimates has remained unaltered. It uses a two leaf process, which estimates photosynthesis as if there were two large leaves on each tree. One leaf is sunlit and the other leaf is shaded. This section of the model uses temperature data to conduct an energy balance for each leaf. From there, the stomatal conductance and intercellular CO_2 concentrations are calculated and then used to find photosynthetic CO_2.

Water stress factors (fw) are used in CLM5 to signify a level of water stress the system is experiencing. In this case, the water stress factor is calculated with leaf water potential, which is a measure of the water availability in vegetation leaves. Leaf water potential is a function of the supply of sap and the evaporative demand, so stress can form from low soil moisture or high VPD. Previous models have not included VPD as a component of water stress factor, so this development is key to improving water stress representation.

The water stress factor is used to calculate many variables in CLM5. It is multiplied by the "well-watered rate" of the maximum carboxylation. The resulting Vcmax (maximum rate of carboxylation) is altered to reflect water stress and decline and is subsequently used to calculate photosynthesis. The water stress factor is also used in the calculation of water demand. Additional variables calculated include root water uptake, vegetation water potential, and water supply. All three variables are calculated using Darcy's Law.

With each of these variables, the PHS configuration of CLM5 is able to balance the resulting vegetation water potential with root water uptake and water demand. It maintains a stable flow between each part of the model, to prevent disconnect between supply and demand. It does have limitations, since it largely simplifies plant hydraulics and there's uncertainty as to how best incorporate the water stress factor into the model. The addition of plant hydraulics to CLM also adds complexity to the model, but it has also been found to align better with observations than past models have. It improves our ability to model hydro-vegetation dynamics, and it incorporates more physics-based modeling than CLM has previously.

3. Data Needs

To run the plant hydraulics section of the Community Land Model, numerous inputs are needed. Plant water supply, which is modeled using Darcy's Law, requires the hydraulic conductance (s-1), the area (m2/m2), and the gradient in water potential (mmH2O) (CLM5.0 User's Guide). These inputs are used to calculate the flux of water (mmH20/s). To further finetune the hydraulic conductance, the maximum segment conductance (s-1), water potential at 50% loss of conductivity (mmH2O), and the water potential of the lower segment terminus (mmH2O) are also needed.

To calculate the stem-to-leaf equations, the flux of water from stem to sunlit leaf (mmH2O), flux of water from stem to shaded leaf (mmH2O), sunlit leaf area index (m2/m2), shaded leaf area index (m2/m2), stem water potential (mmH2O), sunlit leaf water potential (mmH2O), and shaded leaf water potential (mmH2O) are all needed. Additional parameters include maximum leaf conductance (s-1), maximum leaf conductance (s-1), water potential at 50% loss of conductance (mmH2O), and vulnerability curve shape-fitting parameter.

To run the root-to-stem equations, the flux of water from root to stem (mmH2O), stem area index (m2/m2), gravitational potential (mmH2O), root water potential (mmH2O), and stem water potential (mmH2O) are needed. Other parameters include maximum stem conductivity (m/s), water potential at 50% loss of conductivity (mmH2O), and vegetation height (m).

The soil-to-root section requires flux of water from soil layer i to root (mmH2O), change in gravitational potential from soil layer i to surface (mmH2O), total leaf area index (m2/m2), steam area index (m2/m2), water potential in soil layer i (mmH2O), root water potential (mmH2O), root fraction in soil layer i, and the Brooks-Corey soil conductivity in soil layers i (m/s). Also, the length of root tissue conducting path is needed, which is calculated by adding the soil layer depth and the root lateral length in meters. Additional parameters include the root-to-shoot ratio.

Finally, to run the plant water demand section, the sunlit leaf transpiration rate (mm/s), shaded leaf transpiration rate (mm/s), sunlit leaf transpiration absent water stress rate (mm/s), shaded leaf transpiration absent water stress rate (mm/s), sunlit leaf water potential (mmH2O), shaded leaf water potential (mmH2O) are needed. So are the sunlit transpiration water stress, shaded transpiration water stress, stomatal conductance of water corresponding to Esun, stomatal conductance of water corresponding to Eshade, stomatal conductance of water corresponding to Esun,max, and stomatal conductance of water corresponding to Eshade,max variables.

4. Calibration

From my understanding, the model is not internally calibrated, however, users of the model can calibrate it themselves. Several studies have aimed to calibrate and/or validate the model. Denager et al. (2023) evaluated CLM5 on the basis of plant hydraulic parameter optimization. They conducted their experiment using data spanning six years from an agricultural observatory in Denmark. They found that soil texture, summer monthly leaf area index, stomatal conductance, and root distribution have the largest influence on local simulation results. They also found that during calibration, the model overestimated soil moisture and sensible heat flux. Other studies have also calibrated the model, focusing on the CLM as a whole or other subsections of the model (Cheng et al., 2021; Dombrowski et al., 2022). Cheng et al. (2021) chose to understand biases in CLM all together and in doing so also noticed a bias from soil. They also observed that vegetation physiology and phenology influenced energy fluxes which impacted the model further.

5. Numerical Experiment and Design

My numerical experiment takes inspiration from Kennedy et al. (2019). Kennedy et al. (2019) focuses on comparing the PHS and SMS configurations of CLM in a tropical rainforest in the eastern Amazonia. They run four simulations, two of PHS and two of SMS, in order to quantify which configuration performs best in a variety of categories. They found that PHS generally performs much better. Both models have similar amounts of small errors, but SMS had many more large errors compared to PHS. In running the four simulations, they also collected data for numerous output variables. My numerical experiment aims to build on and primarily enhance these results.

As established previously, we know that climate-change enhanced soil moisture dryness and changing vapor pressure deficits are major causes of vegetation stress (Ficklin, & Novick, 2017; McDowell et al., 2015). Understanding these stressors is vital to understanding the full scope of impact of climate change on vegetation dynamics. My study aims to analyze some of these effects in two different ecosystems over a longer period of time under varying climate scenarios. Ideally, we would be able to see how vapor pressure deficit and soil moisture changes over time in both an arid region and a humid environment.

This experiment would be conducted in the Reynolds Creek Experimental Watershed in Idaho and the Sleepers River Research Watershed in Vermont. These watersheds offer very different environments. Reynolds Creek is an arid sagebrush-grassland landscape that transitions to conifers at higher elevations and is used as rangeland (Slaughter et al., 2001). Sleepers River is primarily forested with some dairy pastures (Shanley et al., 2015). They are both longstanding research watersheds with large, long-term hydrologic-related data.

I plan to have three simulations for each watershed, totaling to six simulations. I would like to include a low emissions scenario, medium emission scenario, and high emission scenario. My simulations will run from the years 2000 to 2099. The first 25 years will be used to validate the model and assess errors between simulated values and observational values. Afterwards, the simulation will be used to interpret how vapor pressure deficit and soil moisture changes on an annual basis. CLM5 simulates daily measurements of both vapor pressure deficit and soil moisture, but it might make sense to use annual measurements given this simulation would analyze an entire century. If there are several years that seem particularly interesting, observing daily timesteps could be of use.

Kennedy et al. (2019) input 15 parameter values and left the remaining parameter values as r270 CLM5's default values. Given data limitations, it would make sense to evaluate data availability at each location and input as many parameters as the data allows. However, if there are missing values, default values can be used for this simulation.

I expect there will be changes in both soil moisture and vapor pressure deficit over the course of this century. I hypothesize that soil moisture would decline in both watersheds, but the timing in which the decline will be most prominent will differ. I also hypothesize that vapor pressure deficit will change over time in both watersheds but especially in the Sleepers River Research Watershed. By conducting this experiment, we will have a better understanding of how both variables will be influenced by climate change and will thus have a better understanding of potential impacts of climate change on vegetation.

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