On Determining Wood Thermal Diffusivity and Probe Geometry Using In-Situ Heat Response Curves from Sap Flow Measurements

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Abstract

The heat pulse method is widely used to measure water flux through plants; it works by inferring the velocity of water through a porous medium from the speed at which a heat pulse is propagated through the system. No systematic, non-destructive calibration procedure exists to determine the site-specific parameters necessary for calculating sap velocity, e.g., wood thermal diffusivity and probe geometry. Such parameter calibration is crucial to obtain the correct transpiration flux density from the sap flow measurements at the plant scale; and consequently, to the up-scale of tree-level water flux to the canopy and landscape scales.

The purpose of this study is to present a statistical framework to estimate wood thermal diffusivity and probe geometry simultaneously using in-situ measurements of temperature traces following a heat pulse. The parameters are inferred using a Bayesian inversion technique, based on the Markov chain Monte Carlo sampling method. The primary advantage of the proposed methodology is that it does not require known probe geometry or any further intrusive sampling of sapwood. The Bayesian framework also enables direct quantification of uncertainty in estimated sap flow velocity.

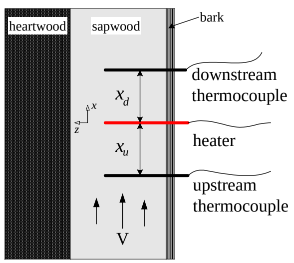
Experiments using synthetic data show that multiple tests on the same apparatus are essential to obtain reliable and accurate solutions. When applied to field conditions, these tests are conducted during different seasons and seasonality of wood thermal diffusivity is obtained as a by-product of the parameter estimation process. Empirical factors are introduced to account for the influence of non-ideal probe geometry on the estimation of heat pulse velocity, and they are estimated as well. The proposed methodology is ready to be applied to calibrate existing heat ratio sap flow systems at other sites. It is especially useful when alternative transpiration calibration devices such as lysimeter are not available.

I. Introduction

Site Information

- Located on the lower foothill of the Sierra Nevada
- Annual precipitation ~ 560mm
- Mean annual air temperature ~ 16.6^{o}C
- Hot and dry in summer, cold and wet in winter
- Deciduous oak trees coexist with annual grasses
- Eddy covariance system installed
- Sap flow measurements on representative trees

Fundamentals of Sap Flow Measurements



heat pulse velocity: $v_h = \frac{\kappa}{x}\ln\frac{\Delta T_d}{\Delta T_u}$

sap velocity: $v_s = \frac{\rho c}{a \rho_s c_s} v_h$

sap flux density: $J_s = a v_s$

sap flux: $Q_s = J_s A$

Objectives of Study

- To provide a non-destructive methodology to determine wood thermal diffusivity (κ) and probe geometry for the sap flow measurements
- To account for impact of asymmetric probe alignment on estimating v_h
- To quantify the uncertainties in estimated v_h

II. Theoretical Background

Heat Transport Equation

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}\right) - v_h\frac{\partial T}{\partial x} + Q\delta(x)\delta(y)\delta(z)\delta(t)$$

Idealized Solution (Marshall, 1958)

- Assume infinite medium and line heater, instantaneous heating

$$\Delta T(x,y,t) = \frac{q}{4\pi\rho c\kappa t}\exp\left[-\frac{(x-v_h t)^2+y^2}{4\kappa t}\right]$$

Improved Solution

- Assume finite dimension of medium and heater, pulsed heating

$$\Delta T(x,y,z,t) = \frac{q'}{\pi\rho c\kappa}\sum_{n=1}^{\infty}\left\{\frac{\sin(b_n a)\cos(b_n z)}{2b_n L+\sin(2b_n L)}\times \int_{t-t_0}^{t} s^{-1}\exp\left[-\frac{(x-v_h s)^2+y^2}{4\kappa s}-\kappa b_n{}^2 s\right]ds\right\}$$

The difference between the idealized solution and improved solution is only significant for times shortly after the heat pulse

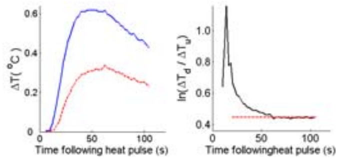
Heat Pulse Velocity

- Symmetric probe alignment: $v_h = \frac{\kappa}{x}\ln\frac{\Delta T_d}{\Delta T_u}$
- Asymmetric probe alignment: $v_h = B_0 + B_1\frac{\kappa}{x}\ln\frac{\Delta T_d}{\Delta T_u}$

with B_0 and B_1 dependent on probe geometry

III. Parameter Estimation Method

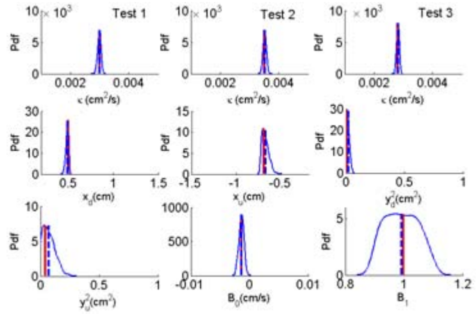
- Conditioned on temperature traces following heat pulse
- Marshall's solution used to fit the data for t>20s
- Heat pulse velocity for asymmetric probe setup embedded
- Bayesian inversion technique based on Markov chain Monte Carlo (MCMC) sampling method implemented



IV.Results and Discussions

Model Verification

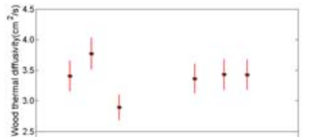
- Synthetic data generated from Marshall's solution
- Three tests with different thermal diffusivity and heat pulse velocity
- Inversion results shown reduced parameter uncertainty
- For thermal diffusivities, both mean and mode close to true value
- For probe geometries, modes are closer to the true values
- More accurate results can be obtained with exact geometry known

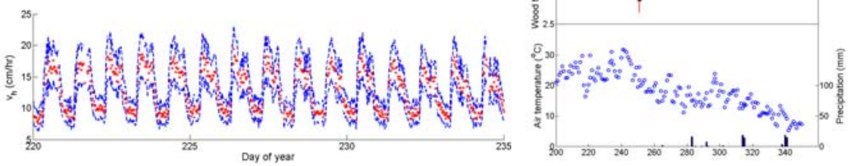


Posterior distributions of parameters. The limits of x-axis represent the bounds imposed on parameters as prior distributions. The solid vertical lines represent the true parameter values and dashed vertical lines are the mean values calculated from the posterior distributions.

Applications to Field Data

- Seasonality of thermal wood diffusivity captured
- Uncertainty in estimated heat pulse velocity directly quantified





V. Conclusions

- Reliable statistical distributions of the parameters are obtained in synthetic study using multiple tests conducted on the same apparatus.
- The uncertainties in the estimated parameters can be reduced by introducing additional knowledge on heat amount input to the system or probe geometry.
- The parameter estimation framework is used to obtain seasonality of wood thermal diffusivity by conducting heat response experiments over different seasons.
- It is highly recommended that any study involving sap flow measurements take temperature response curves routinely to improve the data accuracy.

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