SIMULATED SEASONAL SPATIO-TEMPORAL PATTERNS OF SOIL MOISTURE, TEMPERATURE, AND NET RADIATION IN A DECIDUOUS FOREST

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1. INTRODUCTION

The temperature and moisture regimes in a forest are key components in the forest ecosystem dynamics. Observations and studies indicate that the internal temperature distribution and moisture content of the tree influence not only growth and development, but onset and cessation of cambial activity[1], resistance to insect predation[2], and even affect the population dynamics of the insects[3]. Moreover, temperature directly affects the uptake and metabolism of pollutants from the soil into the tree tissue[4]. Additional studies show that soil and atmospheric temperatures are significant parameters that limit the growth of trees and impose treeline elevation limitation[5].

Directional thermal infrared radiance effects have long been observed in natural backgrounds[6]. In earlier work, we illustrated the use of physically-based models to simulate directional effects in thermal imaging[7-8]. In this paper we describe the simulated spatial and temporal patterns of soil moisture, temperature, and net radiation in a deciduous forest using our recently developed three-dimensional, macro-scale computational tool that simulates the heat and mass transfer interaction in a soil-root-stem system (SRSS). The SRSS model includes the coupling of existing heat and mass transport tools to simulate the diurnal internal and external temperatures, internal fluid flow and moisture distribution, and heat flow in the system.

2. METHODS

We simulate a tree and its root system in the SRSS as three different functional materials; the bark, xylem (sapwood), and heartwood. The bark material is the outer covering of the tree consisting of dead phloem cells, which are air-filled sieve-tube cells that are thermally less conductive than the other materials in the trunk or stem and hydraulically non-conductive. The second material, the xylem, is the living, hydraulically active part of the wood that is responsible for the transport of fluid (water and nutrients) from the roots into the rest of the plant. The innermost material is the heartwood. The heartwood provides structural support to the tree and is composed of dense dead xylem cells that are typically not hydraulically conductive. The root system is derived from measurements of excavated roots of a tree system (Figure 1a). The tree and root system is embedded in a soil that has properties of typical sandy silt (Figure 1b). A diurnally varying flow function is imposed on the upper boundary of the stem that was derived from an average of fluid velocities measured in-situ. The three dimensional distribution of water and temperature in the soil is accomplished by approximating Richards' equation[9] and heat conduction and convection equations, respectively. Soil properties include porosity, hydraulic conductivity, pressure heat, thermal conductivity, spectral emissivity and reflectivity. Surface heat exchange of the soil includes net radiative energy, sensible heat, latent heat, and heat from precipitation events.

Radiative heat transfers are calculated by the Monte Carlo method. Energy flux is emitted, scattered, and reflected around the system until the energy is either absorbed or exits the system. At the short wavelengths, the source term is primarily solar illumination, while at the longer wavelengths; the energy is emitted by all surfaces in the system. Two modes of the Monte Carlo method are used here, forward Monte Carlo method for longwave radiation and backward Monte Carlo method for shortwave radiation. The two methods are applied in this manner primarily for computational benefits. In the case where there are a large number of emitting surfaces, the forward Monte Carlo method is the most computationally efficient and conversely in the case of a few emitting surfaces, the backward Monte Carlo method is more efficient[10].

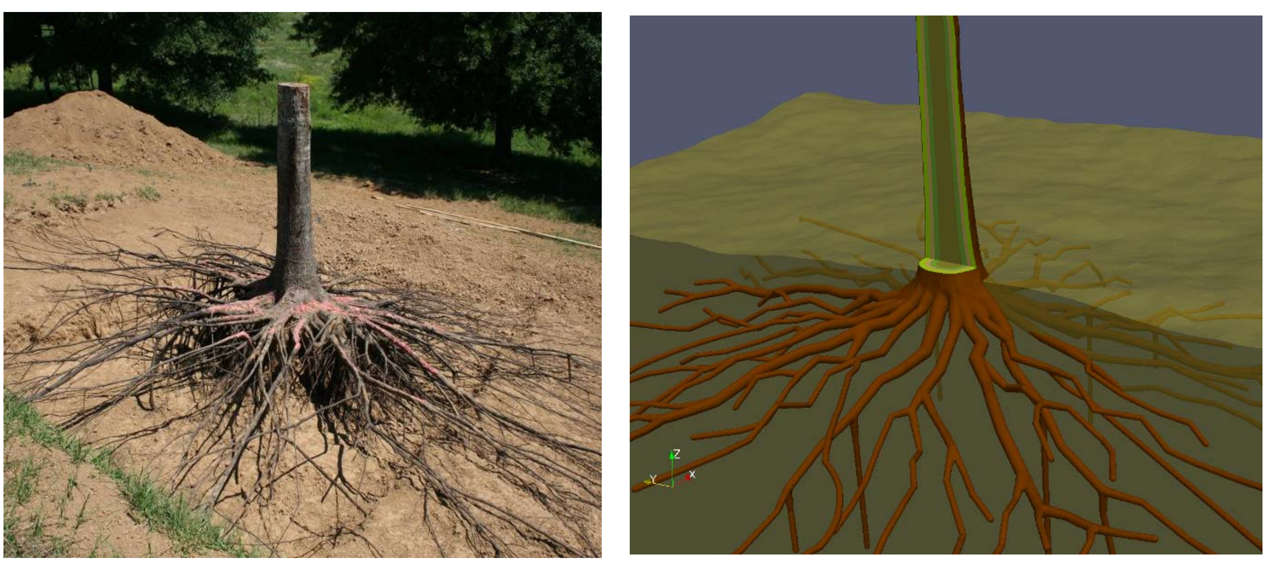

Fig. 1. Photograph of the excavated root system and corresponding computational domain

3. RESULTS

The simulation was executed on a Cray XT4 computer system using 1072 processors and was driven with measured meteorological data collected 2-3 May 2010. The simulation was setup with a measured soil temperature depth profile and the soil saturated with fluid by specifying the water table to be just below the surface of the soil. Figure 2 illustrates the cross-section sap velocity, distribution of surface net radiation, and unsaturated soil region. Figure 3 illustrates the resulting growth of the unsaturated soil region in the soil caused by the transpirational uptake of the tree and root system. The desaturated region begins at the surface of the soil and gradually increases across the surface and down toward the root system. Flow velocities remain constant until the unsaturated region surrounds the root. At that point the hydraulic conductivity of the soil decreases and the flow rate decreases for that part of the root structure but at the same time flow rates increase for roots still in saturated soil regions. Satellite observations offer valuable tools for land remote sensing of global change [11-12], but the highly dynamic and spatially varying nature of the radiant fluxes illustrated here present challenges in appropriately interpreting these observations.

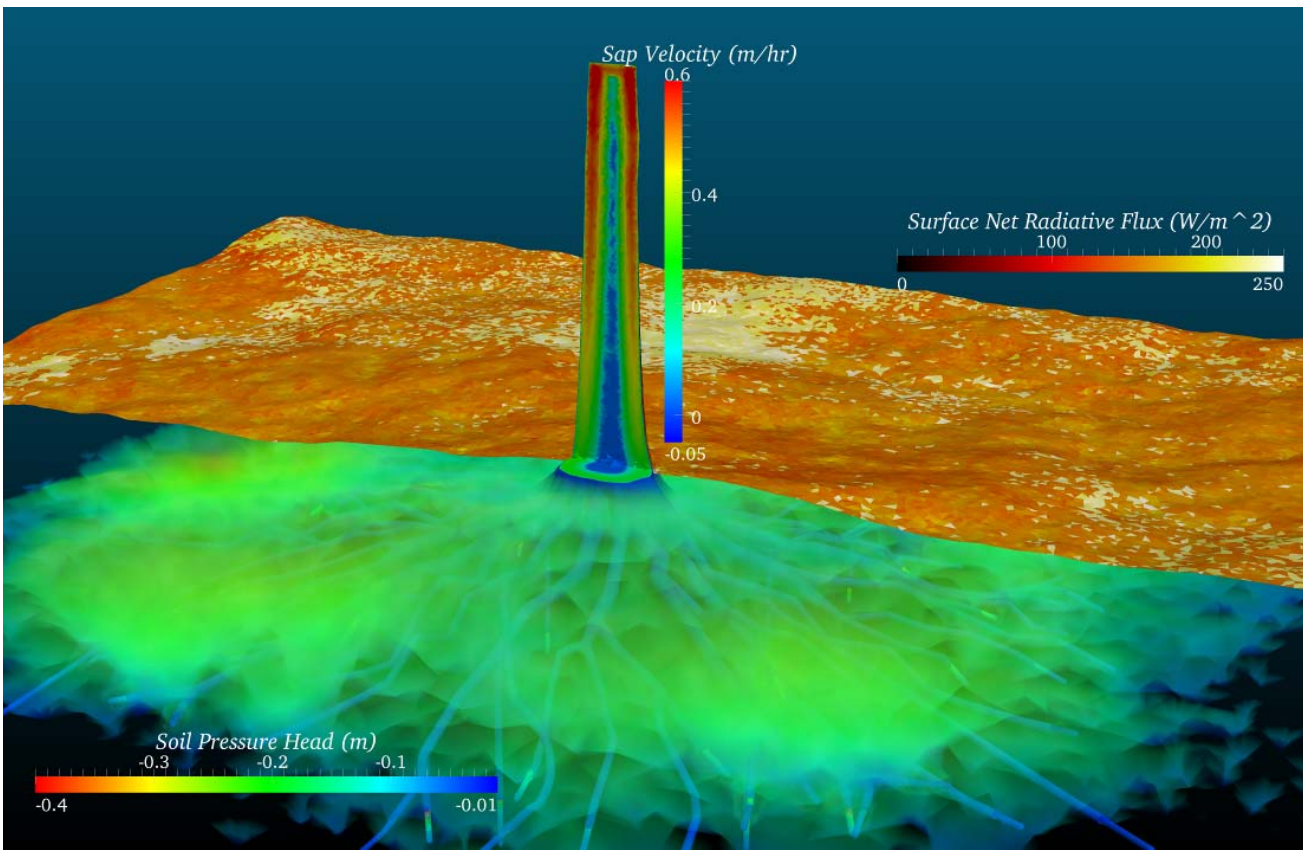

Fig. 2. Combined results of the spatially varying soil moisture, temperature, fluid velocity, and surface net radiation.

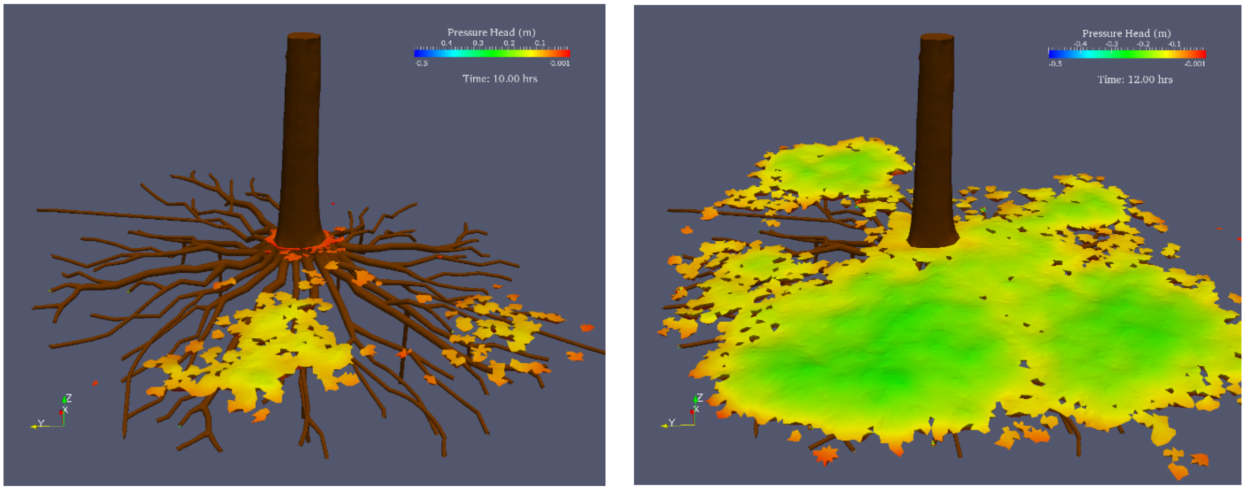

Fig. 3. Growth of the unsaturated soil region due to fluid uptake by the root system from 1000 hrs to 1200 hrs.

REFERENCES

[1] J.-w. Seo, *et al.*, "Estimating the onset of cambial activity in Scots pine in northern Finland by means of the heat-sum approach," *Tree Physiology,* vol. 28, pp. 105-112, 2007.

[2] C. A. Geiger and A. P. Gutierrez, "Ecology of Heteropsylla cubana (Homoptera: Psyllidae): Psyllid Damage, Tree Phenology, Thermal Relations, and Parasitism in the Field.," *Environmental Entomology,* vol. 29, pp. 76-86, 2000.

[3] B. Wermelinger and M. Seifert, "Analysis of the temperature dependent development of the spruce bark beetle Ips typographus (L.) (Col., Scolytidae)," *Journal of Applied Entomology,* vol. 122, pp. 185-191, 1998.

[4] Y. Ouyang, "Phytoremediation: modeling plant uptake and contaminant transport in the soil-plant-atmosphere continuum," *Journal of Hydrology,* vol. 266, pp. 66-82, 2002.

[5] C. Körner and G. Hoch, "A Test of Treeline Theory on a Montane Permafrost Island," *Artic, Antarctic, and Alpine Research,* vol. 38, pp. 113-119, 2006.

[6] L. K. Balick and B. A. Hutchinson, "Directional thermal infrared exitance distribution from a leafless deciduous forest," *IEEE Transactions on Geosciences and Remote Sensing,* vol. 24, pp. 453-458, 1986.

[7] J. A. Smith and J. Jerrell R. Ballard, "Thermal infrared hot spot and dependence on canopy geometry," *Optical Engineering,* vol. 40, pp. 1435-1437, 2001.

[8] J. A. Smith, *et al.*, "Effect of three-dimensional canopy architecture on thermal infrared exitance," *Optical Engineering,* vol. 36, pp. 3093-3100, 1997.

[9] S. E. Howington, *et al.*, "A Suite of Models for Producing Synthetic, Small-scale Thermal Imagery of Vegetated Soil Surfaces," presented at the Proceedings of CMWR XVI International Conference for Computational Methods in Water Resources, Copenhagen, Denmark, 2006.

[10] M. F. Modest, "Backward Monte Carlo Simulations in Radiative Heat Transfer," *Journal of Heat Transfer,* vol. 125, pp. 57-62, 2003.

[11] C. O. Justice, *et al.*, "The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research," *IEEE Transactions on Geosciences and Remote Sensing,* vol. 36, pp. 1228-1249, 1998.

[12] Y. Yamaguchi, *et al.*, "Overview of advanced spaceborne thermal emission and reflection radiometer (ASTER)," *Geoscience and Remote Sensing, IEEE Transactions on,* vol. 36, pp. 1062-1071, 2002.