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Canopy skin temperature variations in relation to climate, soil temperature, and carbon flux at a ponderosa pine forest in central Oregon

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ABSTRACT

Thermal infrared (TIR) techniques to collect thermal imagery have been useful for recording quasi-continuous plant surface temperatures. In this study, we applied a thermal camera to measure canopy skin temperatures in a mature ponderosa pine forest in central Oregon over one growing season from May to September 2014. This study had the following objectives: (1) to examine spatial and temporal variations of canopy temperature; (2) to explore the effects of climate and soil conditions on canopy temperature; and (3) to quantify the relationships of canopy temperatures to forest-atmosphere heat and carbon fluxes. The temporal variation of 30-min mean canopy temperature was large, and leaf temperatures ranged from −2.1 to 33.6 °C during the study period. The temperature difference was small between the whole canopy and leaf regions, while tree stems had warmer temperatures than leaves, especially during the afternoon (12:00–19:59 h). The canopy thermal regime was largely controlled by climatic conditions and related to the soil thermal states. Air temperature, relative humidity, longwave radiation, and soil temperature at 2-cm depth were tightly correlated with 30-min and daily/sub-daily mean canopy leaf temperatures ($r \geq 0.6$ or ≤ -0.6, $p < 0.01$). The daily/sub-daily mean canopy temperatures contained stronger relationships with the climatic and soil variables than the 30-min mean temperatures. During the afternoon, the mean leaf temperature was more closely related to net ecosystem exchange ($r^2 = 0.69$) than air temperature, driven by the strong relationship between tissue temperature and photosynthesis and respiration. Our results show that canopy thermal conditions can be monitored almost continuously for extended time periods to better characterize how canopies respond to environmental conditions. Finally, thermal measurements show great promise for quantifying linkages to carbon exchange in forest ecosystems.

1. Introduction

Temperature is an important environmental variable that strongly affects the physiology of plants and a variety of biogeochemical mechanisms in forest ecosystems (Harley et al., 1996; Medlyn et al., 2002; Scott-Denton et al., 2003; Tierney et al., 2003). Air temperature has been typically used as a thermal metric to study the enzymatic and organismal response of forest canopies to changes in climate and environment (Ball et al., 1994; Tanja et al., 2003). However, forest canopies can be uncoupled from their surroundings (Jarvis and McNaughton, 1986), with substantial deviations between leaf and air temperature. Measurement of leaf and branch surface temperatures should be more directly related to biophysical and physiological reactions and states of forest canopies (Amani et al., 1996; Leinonen and Jones, 2004). The deviation of canopy temperature from air temperature can vary by meteorological and environmental conditions of the forests, resulting from the physiological response in trees. The temperature deviations have been frequently used as an index of drought and water-related stress in agricultural studies (*e.g.* West et al., 1988; Sepulcre-Cantó et al., 2006), while this has been explored far less in the forest ecosystems. Canopy temperature measurements thus represent a promising approach for interpreting and integrating biochemical, physiological, hydrological, and biogeochemical processes in forests.

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It is particularly important to understand how canopy leaf temperatures vary due to abiotic climatic and environmental conditions as well as leaf size and canopy position. For example, canopy temperature and various ecosystem functions (*e.g.* evapotranspiration and photosynthesis) are strongly interrelated with each other, and are non-linearly related to temperature. As global warming increasingly affects forest ecosystems (Bonan, 2008), measurements of canopy temperature should be useful for analyzing how climate change influences ecosystem functions. Longer temporal records of canopy temperature data are required for understanding variation in physiological and biogeochemical processes in forests. To our knowledge, no study has made based on quasi-continuous *in-situ* measurements of forest canopy temperatures over the growing season or year. A primary reason is limited technical capability, but recent advances have produced compact, reliable, and durable instruments for the temperature measurement.

The advance of thermal infrared (TIR) imaging enables us to measure organismal surface temperatures more broadly and frequently (*e.g.* Jones, 2004; McCafferty, 2007; Hristov et al., 2008). TIR techniques using thermal cameras to collect imagery have been applied to record plant surface temperatures of temperate forests for 2–3 days (Leuzinger and Körner, 2007; Scherrer et al., 2011) and alpine landscapes for periods of four days to several weeks (Scherrer and Körner, 2010, 2011). The analyses showed clear differences in surface temperature due to topographical variation (Scherrer and Körner, 2010), distribution of tree species and plant functional types, *i.e.* coniferous *vs*. deciduous trees (Leuzinger and Körner, 2007), as well as the surrounding environment (*e.g.* urban *vs*. rural surroundings) (Leuzinger et al., 2010). Maes et al. (2011) suggested that plant-water relations and water deficits were affected by leaf angle and size as key characteristics of plant species. TIR measurements by Scherrer et al. (2011) revealed that drier areas, resulting from topographical variation, are more likely to experience dryness and thus additional warming in the future. However, determining how climate variability and extreme climate events, such as heat waves, droughts, and frosts, influence the variability of forest canopy temperatures has not been addressed previously.

To date, monitoring of canopy temperatures using TIR imaging has been used primarily to examine the status and regulation of stomatal conductance and its influence on water vapor (H_2O) and carbon dioxide (CO_2) exchanges (Collatz et al., 1990; Fischer et al., 1998; Jones et al., 2009). During the last several decades, a variety of such short-term TIR studies on stomatal conductance have been conducted in agricultural fields (*e.g.* Jackson et al., 1981; Cohen et al., 2005; Möller et al., 2007), with a goal of assisting water management of croplands through optimized irrigation and water stress reduction. Similar TIR monitoring of forest ecosystems would enhance understanding of relations among forest canopy temperature, stomatal conductance, and energy, water, and carbon exchanges.

At the scale of individual leaves, temperature variations result from physical and biological interactions that are affected by leaf morphology and albedo, canopy position, radiation, wind, and stomatal response to the environment (Jones, 2004; Leuzinger and Körner, 2007). These interactions always vary in time and space, so the temporal and spatial scales must be defined to delineate biotic and abiotic processes. In order to describe details of diurnal or seasonal patterns of canopy temperatures and their relationships with environmental variables in ecosystems, continuous TIR monitoring over several months or a year from the same location is required. Moreover, TIR monitoring allows us to measure temperatures across a large forest canopy, thus extending the spatial scale in comparison to traditional measurements of leaf temperatures using thermocouple arrays. By applying TIR imaging, research into the composition of forest canopies (*e.g.* leaves and trunks) and the spatial variability of canopy temperature can be pursued. This work thus focuses on quantifying the spatial and temporal changes in thermal regimes from a forest canopy across a fairly long time period that spans most of one growing seasons.

In this study, we used TIR imagery to measure canopy temperatures in a mature ponderosa pine forest in the Pacific Northwest of the USA. This site provided an opportunity to explore correlations among canopy temperature, climatic and soil variables, as well as energy (sensible and latent heat) and carbon fluxes. The objectives of this study were: (1) to examine spatial and temporal variations of canopy temperature in a mature coniferous forest; (2) to investigate the effects of climatic and soil factors on spatial and temporal variations of canopy temperature; and (3) to interpret the relationships of canopy temperatures to heat and carbon fluxes from this forest. We hypothesized that: (1) there would be considerable temporal and spatial variability in canopy temperatures, as they are strongly affected by multiple climatic and soil variables, such as insolation, air temperature, humidity, and soil moisture; and (2) significant correlations between canopy temperatures and heat and carbon fluxes would be revealed. To our knowledge, this study is the first attempt to measure multi-day canopy surface temperatures using near-surface TIR approaches from a coniferous forest with simultaneous eddy covariance measurements.

2. Methods and materials

2.1. Study site

This study was conducted in a mature coniferous forest in central Oregon that is located within the Cascade Mountains near the city of Sisters at an elevation of 1253 m (44.45°N, 121.56°W) (Fig. 1). The study forest has been privately owned and well protected after harvest in the early 20th century. This forest is named the Metolius mature ponderosa pine forest and was designated as a core research site in the AMERIFLUX network (http://ameriflux.lbl.gov, site US-Me2) where microclimate and eddy covariance flux measurements are collected from a flux tower. The overstory consists of ponderosa pine trees (*Pinus ponderosa* Dougl. Ex P. Laws) with scattered cover from a few incense cedars (*Calocedrus decurrens* (Torr.) Florin). Mean stand age is 65 years in 2015, and the oldest 10% of trees are 100 years. Trees are homogeneously distributed and a typical leaf area index (LAI) is 2.8 $m^2\,m^{-2}$. Average tree height and density are 22 m and 325 trees ha^{-1}, respectively (Irvine et al., 2008; Thomas et al., 2009). The understory is sparse and primarily composed of antelope bitterbrush (*Purshia tridentata* (Pursh) DC.) and greenleaf manzanita (*Arctostaphylos patula* Greene). LAI of the understory is 0.2 $m^2\,m^{-2}$ (Thomas et al., 2009). Soils are ultic haploxeralfs, freely draining sandy loam derived from volcanic ash (69/24/7% sand/silt/clay at 0–0.2 m), and soil depth is approximately 1.5 m (Schwarz et al., 2004; Irvine et al., 2008). The forest is nearly homogenous in all directions to a few kilometers, except an area to the north within an 1 km from the flux tower that was logged in 2005 (Thomas et al., 2009). The climate is semi-arid, with warm/dry summers and cool/wet winters. Most precipitation at the site falls as snow or rain during the winter and spring (between November and April). Annual mean air temperature ranged from 6.7 to 8.0 °C, and mean annual total precipitation varied from 194 to 728 mm in the period from 2002 to 2012. Additional descriptions of the study site are found in Law et al. (2001) and Anthoni et al. (2002).

A 34-m scaffold flux tower was constructed in 2001 for climate and flux observation, and physiological measurements were initiated in the same year (Schwarz et al., 2004; Irvine et al., 2008; Thomas et al., 2009). Numerous climatic variables, fluxes, and concentrations of water vapor (H_2O) and carbon dioxide (CO_2) have