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Wind and plume thermodynamic structures during low-intensity subcanopy fires

Daisuke Seto[a,*], Tara M. Strand[b], Craig B. Clements[a], Harold Thistle[c], Robert Mickler[d]

[a] Fire Weather Research Laboratory, Department of Meteorology and Climate Science, San José State University, San José, CA 95192, USA
[b] Scion New Zealand Crown Research Institute, Christchurch, NZ 8041, USA
[c] Forest Health Technology Enterprise Team, USDA Forest Service, Morgantown, WV 6505, USA
[d] Alion Science and Technology, Durham, NC 27713, USA

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ABSTRACT

This paper presents observational results of wind and plume thermodynamic structures measured during low-intensity subcanopy fires. In-situ meteorological data were collected during the two experiments in the Calloway Forest in North Carolina during the early spring 2010 and winter 2011. Plume updraft velocities between 2 and 4 m s^{-1} were mostly observed during the subcanopy fires with fire intensity of 1200–2500 kW m^{-1}. A maximum updraft velocity of 5.8 m s^{-1} and maximum temperature of 100 °C were recorded at the canopy top due to a head fire. Negative vertical velocities observed within the canopy were associated with cooler air temperatures relative to warm smoke plume temperatures during fire passage at the towers. Increased convection due to the head fire resulted in increased downward transport from above the canopy to the surface. Observed cumulative sensible heat fluxes were 52 kW m^{-2} and 169 kW m^{-2} near the surface, and larger values were found at mid canopy heights at both towers. The peak total heat flux of 50 kW m^{-2} and peak radiative heat flux of 18 kW m^{-2} observed in 2010 were associated with a head fire moving toward the sensors, whereas lower values of 19 kW m^{-2} and 9 kW m^{-2} were measured at the tower in 2011 as a result of a backing fire moving away from the sensors.

1. Introduction

Moderate to high intensity nature of forest, grassland, and shrubland fires present great concerns for human hazard, economical loss, and community safety in the wildland–urban interface (Mell et al., 2010; Morvan, 2011). In contrast, less threatening low-intensity subcanopy fires common in small prescription burns, such as those conducted in the southern United States, pose a greater concern for local and regional air quality. Because reduced air quality has significant impact on human health, aesthetic visibility, and transportation over a broad range of spatial and temporal scales, smoke from prescribed agricultural and forest burning has been a major research topic in many countries around the world (Goodrick et al., 2012).

Wind under a forested environment is highly variable, and the presence of fire in the forest further complicates the flow. Heilman et al. (2014) suggest that impact of forest on atmospheric flow and the resulting vertical and horizontal dispersion of wildfire smoke emission may be significant in the lower atmospheric boundary layer. There have been a handful of field measurements documenting in-forest winds including Sullivan and Knight (2001) and Taylor et al. (2004). The focus of these two studies was mainly on larger scale wind variability and the field trials were not designed for fine-scale flow measurements at the fire front. Better understanding of low-intensity subcanopy fire dynamics is necessary to improve current and newly-developed models related to wildfire and prescribed burning smoke plume transport and dispersion.

Plume rise and dispersion models are much improved when more detailed information on fire location, rate of spread, and heat are given to the models. For example, Daysmoke (Achtemeier et al., 2011), designed for the simulation of smoke plumes from fires, requires initial vertical velocity and temperature anomaly as well as effective plume diameter. A recent development of a simple three-dimensional model by Strand et al. (2009), originally designed to simulate pheromone concentrations and transport in a forested environment, potentially allows for prediction of near-source smoke concentrations under different forest canopies. If the model can be used to simulate near-source smoke plume behavior and dispersion in the forest canopy, in-situ wind velocity data

* Corresponding author. Tel.: +1 408 924 5189; fax: +1 408 924 5191.
E-mail address: daisuke.seto@sjsu.edu (D. Seto).

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collected near the heat source (i.e., fire) are necessary to test the performance and reliability of this model. More recently, Heilman et al. (2013) conducted two comprehensive field measurements during low-intensity prescribed fires in forested environments in order to evaluate the capability of existing coupled meteorological-atmosphere dispersion models to adequately resolve small-scale fire-atmosphere and forest interactions. Such observational data can be used to improve our understanding of fundamental fire-atmosphere-canopy interactions that govern fire and smoke plume behavior. Additionally, recent advances in fire-atmosphere coupled models make it possible to resolve small-scale turbulence and fire-atmosphere interactions. In fact, some of the fire–atmosphere coupled models have shown successful reproductions of wind and thermodynamic structures, necessary for smoke plume modeling, observed during a grass fire experiment (Filippi et al., 2013; Kochanski et al., 2013). To date; however, these models and other fire-atmosphere coupled models (e.g. Linn et al., 2010; Coen et al., 2013) have not been used to simulate subcanopy fires and a suite of observational datasets and knowledge regarding fire-atmosphere and canopy interactions are needed to evaluate these and future models. Accurate numerical simulations require realistic heat input values to set up initial conditions, and those values should ideally be obtained through field experiments or numerical results validated in similar conditions.

Both coupled fire-atmospheric and smoke dispersion models benefit from detailed knowledge in fire-induced heat fluxes. Convective and radiative heat fluxes are not only the two main mechanisms for heat transfer that controls fire spread (Butler et al., 2004; Morandini et al., 2006; Silvani and Morandini, 2009; Cruz et al., 2011) but are a direct indication of the fire's intensity. Frankman et al. (2012) measured the convective and radiant heat fluxes from 13 wildfires including surface fires over pine needle fuel. Their results showed the peak radiant heat flux values of 18–77 $kW\,m^{-2}$ while peak convective heat flux values ranged from 13 and 140 $kW\,m^{-2}$. Silvani and Morandini (2009) showed peak radiant and total heat fluxes of 25 and 40 $kW\,m^{-2}$, respectively, over pine needle fuel. Because there is a wide range of the observed heat flux values due to various measurement platforms, further investigation is worthwhile to characterize the heat fluxes based on flame height, fire intensity, or flame geometry. These heat flux values measured under specific wind conditions and in various fuel types in the field are needed for evaluating numerical simulations and improving smoke plume dispersion models (Linn et al., 2010).

Surface sensible heat flux released from the fire also determines the final height that the plume reaches. Sensible heat flux measurements during experimental fires are far more uncommon than convective and radiative heat fluxes, but it is an important parameter in model simulations for representing a fireline as a line source of heat (e.g. Sun et al., 2006; Heilman et al., 2013). Clements et al. (2007) measured the sensible heat flux emitted by a grass fire, which was allowed to burn under the flux tower, and Jenkins et al. (2001) provided estimates of typical sensible heat flux values emitted by a forest fire. Clark et al. (1999) and Coen et al. (2004) measured the sensible heat flux from forest fires using infrared video camera imagery and image flow analysis scheme. While these measurements provided realistic sensible heat flux values that can be used to represent heat output above a wildfire fireline in numerical simulations, these values are from much higher intensity fires than the lower intensity surface fires, suggesting limited usefulness in simulating subcanopy fires. Realistic surface heat flux values are necessary to represent low-intensity fires and subsequent smoke plume transport. Additionally, remote sensing measurements of radiative and/or convective heat from wildfires such as Riggan et al. (2004) provided useful information for simulating plume rise (Freitas et al., 2007; Sofiev et al., 2012), and in-situ heat flux measurements serve necessary data for validating the measurements from above.

The objective of this paper is to present observational results of wind and smoke plume thermodynamic structures measured during low-intensity subcanopy fires. Two in-situ wind and temperature datasets were collected from two prescribed burns that took place in southeastern United States in a longleaf pine forest. These datasets were used to compare winds and plume temperatures for a better understanding of fire and plume behavior similarities and differences in the same forest environment. Total, radiative, and sensible heat fluxes are also discussed to provide some quantitative insight into prescribed fires in forested environment.

2. Field experiment description

2.1. Site and fuel description

Two low-intensity prescribed burns took place on 7 March 2010 and 16 February 2011 at The Nature Conservancy's (TNC) Calloway Forest/Sandhills Preserve in North Carolina, USA (Fig. 1). The experimental burns were surface fires under a longleaf pine canopy (*Pinus palustris* Mill.) sitting on gently rolling terrain of old sand dunes. TNC restores this forest by using prescribed fires to mimic the natural fire-return interval, reduce fuels, and to build a healthy habitat for the endangered red-cockaded woodpeckers. The mean tree height (h_c) was 20 m. The soil was sandy with little to no organic matter beyond the surface duff layer. The surface fuels consisted of longleaf pine litter, both cured and live wiregrass (*Aristida stricta*), American turkey oak (*Quercus laevis*), gallberry (*Ilex glabra*), and regeneration longleaf pine. Although small dead tree stems and branches were present on the ground, they were very few and did not carry the fire. Pre-burn fuel loadings in Burn 1 (2010) and Burn 2 (2011) were 0.78 $kg\,m^{-2}$ and 1.44 $kg\,m^{-2}$, respectively. The managed fire-return intervals over the previous ten years were 2 years on average for Burn 1 and 3 years for Burn 2. The stand density for Burns 1 and 2 was 203 stems ha^{-1} and 348 stems ha^{-1}, respectively. A majority of the stems were approximately 1 m mean diameter at breast height (dbh). Further site and fuel information is summarized in Table 1.

2.2. Weather

Background weather observations were made using upper-air rawinsondes for determining stability and local vertical wind profiles. The rawinsonde sounding was conducted in a large clearing near the burns prior to ignition. For Burn 1, winds were westerly and $<5\,m\,s^{-1}$ up to 1 km above ground level (AGL), while for Burn 2 winds were from southeast to southwest and mostly $<10\,m\,s^{-1}$ from the surface to 1 km AGL (Fig. 2). The mixing height was around 1.5 km AGL for Burn 1 and 1 km AGL for Burn 2, as indicated by a capping temperature inversion and sharp drop in the dewpoint temperature. The atmospheric stability below the mixing height was neutral to weakly stable except near-surface where an unstable superadiabatic layer was observed. A relative humidity of 20% was observed at the tower before ignition of Burn 1 and it ranged from 13% and 18% during the burn. For Burn 2 the relative humidity prior to ignition was 30% and it remained between 35% and 40% throughout the duration of the burn.

2.3. Fire

The burn manager and interior ignition crews controlled the fire by slowing down the interior ignition to cool down the fire when necessary. It kept the flame height relatively low to prevent canopy scorch. Initial backing fires (fire moving against predominant wind