

Atmospheric Turbulence Observations in the Vicinity of Surface Fires in Forested Environments

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ABSTRACT

Ambient and fire-induced atmospheric turbulence in the vicinity of wildland fires can affect the behavior of those fires and the dispersion of smoke. The presence of forest overstory vegetation can further complicate the evolution of local turbulence regimes and their interaction with spreading fires and smoke plumes. Previous observational studies of wildland fire events in forested environments have shown that turbulence energy and anisotropy in the vicinity of spreading line fires exhibit temporal and spatial variability influenced by the presence of overstory vegetation. This study builds on those previous observational studies to further examine turbulence regimes during two wildland fires in forested environments, with an emphasis on the effects of forest canopies on turbulence energy budgets, the skewness in turbulent velocity distributions, and stability–anisotropy variations before, during, and after fire-front-passage periods. Analyses indicate that turbulence anisotropy tends to persist throughout the vertical extent of overstory vegetation layers even during highly buoyant fire-front-passage periods, with horizontal velocity perturbations dominating over vertical velocity perturbations. The analyses also suggest that the periods before and after fire-front passage in forested environments can be very different with respect to how diffusion and shear production concurrently affect the evolution of turbulence energy within the canopy layer. In addition, horizontal and vertical velocity distribution analyses carried out in this study suggest that spreading line fires can have a substantial effect on the skewness of daytime velocity distributions typically observed inside forest vegetation layers.

1. Introduction

Wildland fires often occur in forested environments. Fire spread and smoke dispersion through these environments are affected by ambient and fire-induced atmospheric circulations, which, in turn, are influenced by the presence of forest vegetation (Albini and Baughman

1979; Ryan 2002; Taylor et al. 2004; Kiefer et al. 2014; Seto et al. 2014; Heilman et al. 2015). The properties of atmospheric mean and turbulent circulations inside forest vegetation layers in the absence of wildland fires have been examined extensively in observational and modeling studies (e.g., Wilson and Shaw 1977; Raupach and Thom 1981; Finnigan 2000; Dupont and Brunet 2008; Su et al. 2008; Vickers and Thomas 2013). These studies have provided valuable insight into the atmospheric dynamics occurring within and above canopy layers and

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have laid the foundation for subsequent development of predictive tools that incorporate atmospheric turbulence processes for addressing a variety of environmental issues in forested environments, including seed dispersal (e.g., [Nathan et al. 2011](#)), carbon and water exchanges (e.g., [Baldocchi and Wilson 2001](#)), and pollutant dispersion and deposition (e.g., [Erisman and Draaijers 2003](#)). Until fairly recently, however, observational and modeling studies that are focused on turbulent circulations within and in the vicinity of wildland fires in forested environments have been limited. Improving our understanding of how wildland fires can affect turbulence regimes inside forest vegetation layers is critical for the development of new and improved operational predictive tools and decision-support systems for fire behavior and smoke dispersion that account for canopy-influenced turbulence effects.

With the recent advancement in monitoring techniques for assessing atmospheric conditions within and near wildland fire environments, significant progress has been made in measuring local fire-induced turbulence regimes as wildland fires spread across the landscape. For example, [Clements et al. \(2007, 2008\)](#), [Seto and Clements \(2011\)](#), and [Charland and Clements \(2013\)](#) measured near-surface and lower-boundary layer atmospheric responses, including fire-induced turbulent circulations, to wildland grass fires in flat- and sloping-terrain environments. Building upon the successes of these grass-fire experiments, several wildland fire experiments with components focused on local fire-atmosphere interactions within forested environments have been conducted in recent years to assess the effects of forest overstory vegetation on atmospheric circulations and local plume behavior in the vicinity of spreading surface fires. The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) field campaigns conducted in 2008, 2011, and 2012 in Florida and Georgia ([Ottmar et al. 2016](#)) provided insight into potential ambient and fire-induced atmospheric turbulence effects on surface fire spread through forest stands ([Clements et al. 2016](#)). Similar wildland fire experiments conducted in forested environments in 2010–12 in New Jersey ([Heilman et al. 2013](#)) and North Carolina ([Strand et al. 2013](#)) yielded atmospheric turbulence observations that suggest forest overstory vegetation affects the vertical distribution of turbulent kinetic energy (TKE) above line fires, the amount of anisotropy in the turbulence field, and the directional mixing of heat and smoke ([Seto et al. 2013](#); [Heilman et al. 2015](#)).

The evolution of local atmospheric turbulence regimes in the vicinity of wildland fires in forested environments depends, in part, on the production of turbulent energy due to wind shears associated with

ambient and fire-induced circulations within and above the forest vegetation layer, the production or dissipation of turbulent energy due to local buoyancy, and the vertical diffusion of turbulent energy through the vegetation layer. Observations of turbulent energy budgets inside forest vegetation layers have been reported in the literature (e.g., [Vickers and Thomas 2013](#)), but there is a lack of observations of turbulent energy budgets inside forest vegetation layers when a surface fire is present.

In addition to the lack of observations of turbulent energy budgets in fire and forested environments, there also is a lack of analyses of turbulent velocity distributions that occur in the vicinity of wildland fires in forested environments. Some operational air-quality tools used for predicting smoke dispersion from wildland fires assume Gaussian turbulence regimes [e.g., the California Puff (CALPUFF) dispersion model option within the BlueSky smoke-modeling framework ([Scire et al. 2000](#); [Larkin et al. 2009](#)) and the “FLEXPART” Lagrangian particle dispersion model ([Stohl et al. 2005](#))], implying minimal skewness in horizontal and vertical velocity distributions. Previous studies have shown that horizontal and vertical velocity distributions inside forest vegetation layers can be highly skewed ([Baldocchi and Meyers 1989](#); [Amiro 1990](#); [Leclerc et al. 1991](#)), however, which calls into question the use of Gaussian dispersion models for predicting the local dispersal of gases and particles within forested environments. When wildland fires inside forest vegetation layers occur, the skewness in velocity distributions and the associated non-Gaussian nature of turbulence regimes that characterize that environment are likely to be affected, which in turn can impact energy exchange and how smoke from those fires is dispersed.

The previous study of [Heilman et al. \(2015\)](#) provided information on the spectral characteristics of the horizontal and vertical wind components and turbulence anisotropy before, during, and after the passage of typical low-intensity line fires within forest stands. This study builds upon that previous work and attempts to fill some of the knowledge gaps that exist in our understanding of 1) the variability in turbulence anisotropy that can occur in response to local stability changes associated with spreading line fires in forested environments, 2) the relative contributions of vertical wind shear, buoyancy, and turbulent diffusion to turbulent energy evolution during wildland fire events in forested environments, and 3) the effects of fire-induced circulations on the non-Gaussian nature of turbulence regimes that typically exist inside forest vegetation layers. The observational results for turbulence anisotropy, turbulence budget, and velocity skewness that are presented in this paper also provide valuable data for

evaluating and validating predictive tools for fire–atmosphere interaction that account for atmospheric turbulence dynamics in forested environments.

The remainder of this paper is organized as follows: A brief description of the wildland fire experiments, monitoring strategies, and data-analysis techniques adopted for this study is presented in section 2. In section 3a, a summary of the general ambient and fire-induced meteorological conditions that occurred during the fire experiments and an analysis of how local stability affected turbulence anisotropy in the vicinity of spreading line fires are presented. Presentation and discussion of the contributions to the observed turbulent energy budget by wind shear, buoyancy, and diffusion within and near the fire fronts occur in section 3b. Section 3c provides a summary of the observed skewness in horizontal and vertical velocity distributions that characterized the turbulent circulations during the fire experiments. The paper concludes in section 4 with an overall summary of the results and a discussion of their relevance to predictive tools for fire behavior and smoke dispersion.

2. Methods

a. Fire experiments

As part of a U.S. Joint Fire Science Program project that focused on the development of modeling tools for predicting smoke dispersion during low-intensity wildland fires in forest environments (Heilman et al. 2013), two prescribed fire experiments were conducted in the New Jersey Pinelands National Reserve in March 2011 and March 2012 to measure fire–fuel–atmosphere interactions and to provide data for evaluating coupled meteorological and smoke-dispersion modeling systems. The prescribed fires were carried out in 107-ha (20 March 2011) and 97-ha (6 March 2012) burn blocks with overstory vegetation composed of pitch pine (*Pinus rigida* Mill.), shortleaf pine (*P. echinata* Mill.), and mixed oak (*Quercus* spp.) at ~15–23 m in height and understory vegetation composed of blueberry (*Vaccinium* spp.), huckleberry (*Gaylussacia* spp.), and scrub oaks. Profiles of average plant-area density A_p for the two burn blocks that are based on aerial lidar measurement techniques (Skowronski et al. 2007, 2011) are shown in Fig. 1. Average fuel loading for the understory vegetation and the forest floor in the 2011 burn block was 1485 g m^{-2} , with 43% of the total loading attributed to shrubs and 57% attributed to forest-floor fuels. For the 2012 burn block, the average understory vegetation and forest-floor fuel loading was 1104 g m^{-2} ; only 15% of that loading was attributed to shrubs while 85% was attributed to forest-floor fuels. The 2011 and 2012 burn

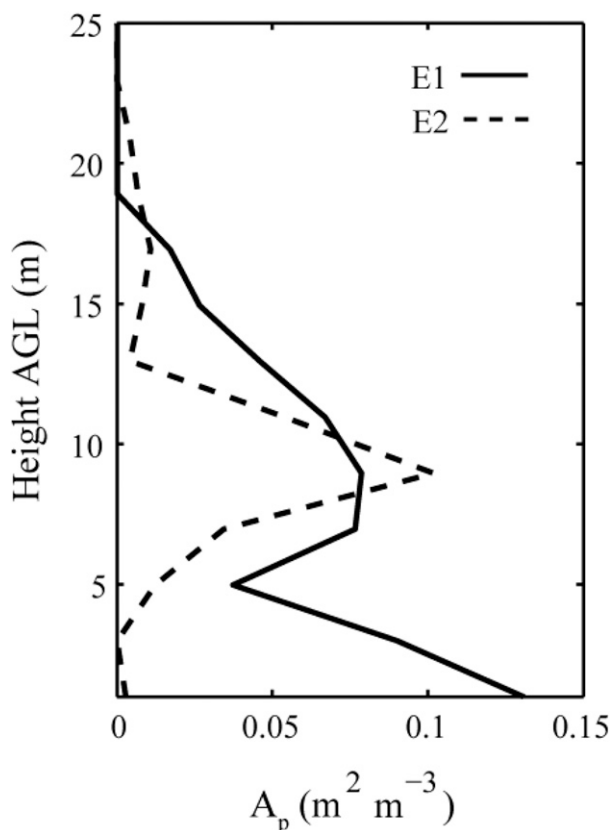


FIG. 1. Estimated profiles of A_p for the 20 Mar 2011 (E1) and 6 Mar 2012 (E2) burn blocks as based on aerial lidar measurements.

blocks were last burned in 1985 (prescribed fire) and 1963 (wildfire), respectively.

Within each burn block, a 10-m tower, a 20-m tower, and a 30-m tower were installed to provide instrument platforms for measuring a suite of meteorological variables within and near the top of the forest overstory vegetation layer. Meteorological and air-quality monitoring systems were mounted on the towers at multiple heights above ground level (AGL) to measure the U and V horizontal wind speed components, the W vertical wind speed component, temperature T , relative humidity RH , net radiation R_n , atmospheric pressure p , radiative heat fluxes R_{hf} , and carbon monoxide (CO) and carbon dioxide (CO_2) concentrations. The respective measurements of wind speed components and temperature on the 10-, 20-, and 30-m towers were accomplished with sonic anemometers (3, 10, 20, and 30 m AGL) and thermocouples (1-m spacing from 0 to 10 m AGL and 2–5-m spacing from 10 m to the tower top on the 20- and 30-m towers) sampled at 10-Hz frequency, allowing for an analysis of turbulent circulations and thermal perturbations across a wide range of spatial and temporal scales.



FIG. 2. Typical backing line-fire characteristics during the (a) 20 Mar 2011 and (b) 6 Mar 2012 fire experiments. The line fire was spreading from left to right in (a) and from right to left in (b).

On the mornings of the 20 March 2011 (1355 UTC) and 6 March 2012 (1430 UTC) fire experiments, the New Jersey Forest Fire Service initiated surface backing line fires with drip torches along the western (in 2011) or eastern (in 2012) boundaries of the burn blocks. The fires were allowed to spread against the prevailing ($<3 \text{ m s}^{-1}$) northeasterly–southeasterly (in 2011) or

northwesterly–southwesterly (in 2012) near-surface winds during the experiments until reaching the up-wind perimeters of the burn blocks (Fig. 2). Fire-line spread rates were approximately 1.50 and 0.33 m min^{-1} for the 2011 and 2012 experiments, respectively, with fire-line widths averaging $1\text{--}2 \text{ m}$. The instrumented tower network set up in each burn block provided

meteorological and air-quality measurements before, during, and after fire-front passage (FFP) at each tower location.

b. Data

The raw 10-Hz wind speed and temperature data collected on the days of the fire experiments and used for the turbulence analyses in this study were subjected to a despiking and filtering routine to remove sporadic erroneous data values and data values that exceeded 6 standard deviations from 1-h running means. Following the application of the despiking and filtering routine, the sonic-anemometer component wind speed data were tilt corrected, following the technique of Wilczak et al. (2001), to minimize potential measurement errors in the vertical velocity that are associated with sonic anemometers not being mounted exactly level on the network towers.

To quantify the ambient and fire-induced atmospheric turbulence regimes and partial turbulence energy budgets that existed before, during, and after FFP at the locations of the 10-, 20-, and 30-m towers, perturbation velocities u' , v' , and w' and temperatures t' were computed every 0.1 s at the heights of the sonic anemometers on the 10-, 20-, and 30-m towers. The perturbations were computed by subtracting 1-h block-averaged component wind speeds $\overline{U}$, $\overline{V}$, and $\overline{W}$ and temperatures $\overline{T}$ from the 10-Hz observed component wind speeds (U , V , and W) and temperatures (T). For this study, 1-h block-averaging periods were adopted on the basis of the recommendation of Sun et al. (2006) for characterizing eddy fluxes in forested environments. As noted in the turbulence spectral analysis study of Heilman et al. (2015), the perturbation velocities and temperatures during the subjectively determined “fire periods” when the spreading line fires were strongly affecting local circulations and temperatures at the tower locations (~ 30 min in duration) were computed on the basis of the mean velocities and temperatures for the 1-h period prior to the onset of the fire periods. This procedure, also used by Seto et al. (2013), produces computed perturbations that are a better characterization of the actual fire-induced turbulence regime near the fire environment.

A full description of the monitoring-network design, instrumentation, burn-block vegetation properties, and data processing used for the two prescribed fire experiments can be found in Heilman et al. (2013).

c. TKE-budget calculations

The temporal variation of TKE at any location depends on a number of physical processes, as discussed by Stull (1988) and shown in the TKE tendency equation below:

$$\frac{\partial \bar{e}}{\partial t} = \frac{g}{\theta_v} (\overline{w't'_v}) - \overline{u'w'} \frac{\partial \overline{U}}{\partial z} - \overline{v'w'} \frac{\partial \overline{V}}{\partial z} - \frac{\partial (\overline{w'e})}{\partial z} - \frac{1}{\bar{\rho}} \frac{\partial (\overline{w'p'})}{\partial z} - \varepsilon. \quad (1)$$

Here, $\bar{e} = \text{TKE} = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$, g is the acceleration of gravity, θ_v is the virtual potential temperature, $\bar{\rho}$ is the air density, p is the atmospheric pressure, and ε is the viscous dissipation of TKE. For this study, the overbars indicate time averages, as opposed to spatial or ensemble averages. The first term on the right side of the equation is the buoyant production or dissipation of TKE, the second and third terms represent the production of TKE as a result of mechanical shear, the fourth term is the turbulent transport (diffusion) of TKE, and the fifth term is the pressure correlation or transport term that quantifies the redistribution of TKE by pressure perturbations (Stull 1988). This equation assumes horizontal homogeneity and that the mean vertical velocity is zero. It also neglects the wake production of TKE from forest vegetation and the dissipation of TKE by canopy drag forces (Kiefer et al. 2013).

Although the assumption of local horizontal homogeneity of atmospheric variables in the vicinity of wildland fires within forested environments is clearly not valid, the available monitoring network used in this study did not allow for adequate measurements of local horizontal variability in atmospheric variables or measurements related to the production or dissipation of TKE resulting from the presence of forest vegetation. Also, measurements of high-frequency pressure perturbations during the fire experiments were not made. Given these limitations in the monitoring network, the TKE-budget analysis for this study focused primarily on the relative contributions of buoyancy, shear (vertical) production, and vertical turbulent transport (diffusion) to TKE evolution [first four terms on the right side of Eq. (1)] within three defined layers (0–3, 3–10, and 10–20 m) before, during, and after FFP at the locations of the network towers. Wind and temperature measurements at the 3-, 10-, and 20-m levels were used to compute the Reynolds stress and vertical heat flux layer-average values along with the horizontal wind component and TKE vertical flux gradients. For the computations in the 0–3-m layer, the wind speed components were assumed to be zero at the surface.

d. Velocity-distribution skewness calculations

The high-frequency (10 Hz) horizontal and vertical velocity components U , V , and W , as measured by the sonic anemometers mounted on the network towers, were used to compute height-dependent skewness values

for the horizontal (Sk_u and Sk_v) and vertical (Sk_w) wind speed distributions as follows:

$$Sk_u = \overline{u'^3} \sigma_u^{-3}, \quad (2)$$

$$Sk_v = \overline{v'^3} \sigma_v^{-3}, \quad \text{and} \quad (3)$$

$$Sk_w = \overline{w'^3} \sigma_w^{-3}, \quad (4)$$

where σ_u , σ_v , and σ_w are the standard deviations of the U , V , and W velocities, respectively, at each tower level. Note that skewness values near 0 characterize Gaussian turbulence regimes (Flesch and Wilson 1992), whereas horizontal and vertical wind distributions inside forest vegetation layers can exhibit skewness values on the order of +1 and −1, respectively (Baldocchi and Meyers 1989; Amiro 1990; Leclerc et al. 1991), an indication of highly non-Gaussian turbulence regimes.

3. Results and discussion

a. Overview of ambient and fire-induced turbulence environments

As with the Heilman et al. (2015) turbulence spectral analyses of the 20 March 2011 and 6 March 2012 prescribed fire experiments, we focused our analyses of anisotropy, turbulence energy budget, and velocity-distribution skewness for this study on measurements made at the 20-m tower sites. These towers were located well within the boundaries of the burn blocks (Fig. 1 in Heilman et al. 2015) where fire-spread rates were less variable. The sonic-anemometer and thermocouple measurements at the 3-, 10-, and 20-m levels on these towers also provided more thorough information on wind and temperature profiles within and near the top of the forest overstory vegetation layer than do the measurements made at the 10- and 30-m towers.

To set the context for the turbulence regime and turbulence energy budget analyses reported in this paper, the observed variations in temperature, wind speed, and turbulence energy that occurred during the fire experiments and that are described in Heilman et al. (2015) are briefly summarized here. Figure 3 [adapted from Fig. 2 in Heilman et al. (2015)] shows the observed 1-min averaged T , horizontal wind speed $[(U^2 + V^2)^{0.5}]$, W , and TKE values before, during, and after FFP at the 20-m towers for both fire experiments [1520 eastern daylight time (EDT) 20 March 2011; 1537 eastern standard time (EST) 6 March 2012].

The periods before FFP for both fire experiments were characterized by slight temporal and vertical variations in temperature, with slightly lower temperatures near the canopy top than within the overstory vegetation layer and near the surface (Figs. 3a,b). Horizontal wind speeds

before FFP were less than 1.5 m s^{-1} within the vegetation layer for both experiments, but near the canopy tops the horizontal wind speeds varied from less than 1 to more than 4 m s^{-1} (Figs. 3c,d). Weak updrafts and downdrafts of generally less than $\pm 0.5 \text{ m s}^{-1}$ occurred before FFP, with the highest magnitudes generally near the canopy tops (Figs. 3e,f). The highest TKE values prior to FFP occurred near the canopy top but were generally less than $5 \text{ m}^2 \text{ s}^{-2}$; TKE values below the canopy top were low, usually less than $1 \text{ m}^2 \text{ s}^{-2}$ (Figs. 3g,h).

During the FFP periods, the temperature, wind speed, and turbulence responses to the advancing line fires were very different for the two experiments because of the substantially different fire intensities that occurred. On the basis of the formulation of Byram (1959), the estimated intensity of the 20 March 2011 fire (325 kW m^{-1}) was considerably higher than that of the 6 March 2012 fire (52 kW m^{-1}), which is consistent with the greater fuel loading (2011: $1485 \pm 388 \text{ g m}^{-2}$; 2012: $1104 \pm 246 \text{ g m}^{-2}$), higher consumption values (2011: 696.2 g m^{-2} ; 2012: 507.3 g m^{-2}), and higher line-fire-spread rates (2011: 1.50 m min^{-1} ; 2012: 0.33 m min^{-1}) that were observed during the earlier fire (Heilman et al. 2013). Although the estimated fire intensities differed substantially, both intensities were in line with the ~ 50 – 500 kW m^{-1} intensities measured or estimated during other prescribed fires conducted in forested environments (e.g., Byram 1959; Smith and James 1978; Alexander 1982) and were much smaller than the $10\,000$ – $30\,000 \text{ kW m}^{-1}$ intensities associated with crown fires (Alexander 1982). Maximum 1-min-averaged near-surface temperatures (3 m AGL) reached $\sim 52^\circ\text{C}$ during FFP for the 20 March 2011 fire as compared with $\sim 17^\circ\text{C}$ for the 6 March 2012 fire (Figs. 3a,b). Associated maximum vertical turbulent heat fluxes at 3 m AGL during FFP for the 2011 and 2012 fires were 23.0 and 3.2 kW m^{-2} , respectively. The fire-intensity differences resulted in different wind speed and TKE responses within and near the top of the forest vegetation layers. The higher-intensity 2011 fire produced substantially larger horizontal and vertical wind speed and TKE responses during and after FFP than the lower-intensity 2012 fire (Figs. 3c–h), with the largest responses occurring near the canopy top (20 m AGL) instead of near the surface. The numerical simulations of the 2011 fire experiment reported by Kiefer et al. (2014) also revealed maximum increases in TKE near the canopy top, and they noted that the substantial increase in TKE values from the midcanopy level (10 m AGL) to just above the canopy top (20 m AGL) corresponded to the relatively large vertical gradients in plant-area density above 10 m that characterized the overstory vegetation in the 2011 burn plot (Fig. 1).

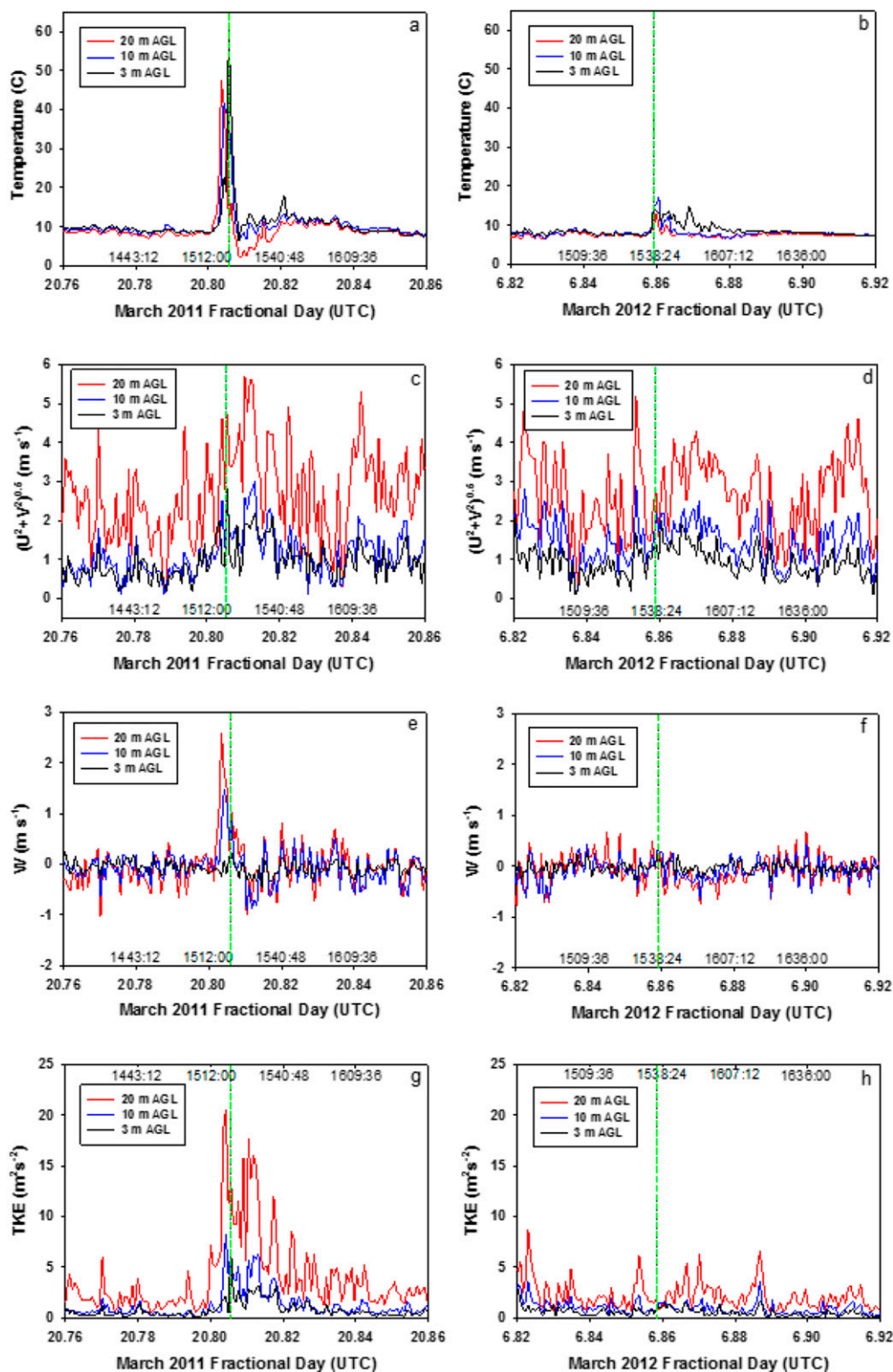


FIG. 3. Observed 1-min averaged (a),(b) thermocouple T , (c),(d) horizontal wind speeds, (e),(f) W , and (g),(h) TKE $[0.5(u^2 + v^2 + w^2)]$ at three levels on the 20-m towers before, during, and after the (left) 20 Mar 2011 and (right) 6 Mar 2012 line fires passed the towers. Vertical green dashed lines indicate times of fire-front passage. Time stamps (hhmm:ss) in EDT (left panels) and EST (right panels) are shown above the lower axes. [This figure is adapted from Fig. 2 in Heilman et al. (2015).]

TABLE 1. Average TKE (m^2s^{-2}) and average anisotropy expressed as $\overline{w^2}/(2 \times \text{TKE})$ observed during defined 30-min pre-FFP, FFP, and post-FFP periods at three height levels (m) on the 20-m towers for the 20 Mar 2011 and 6 Mar 2012 prescribed fire experiments.

Height	Quantity	20 Mar 2011 (EDT)			6 Mar 2012 (EST)		
		Pre FFP (1435–1505)	FFP (1505–1535)	Post FFP (1535–1605)	Pre FFP (1452–1522)	FFP (1522–1552)	Post FFP (1552–1622)
20	TKE	1.7513	8.2165	4.3510	1.9564	2.3715	2.5991
	$\overline{w^2}/(2 \times \text{TKE})$	0.1607	0.1389	0.1399	0.1487	0.1353	0.1103
10	TKE	0.5641	2.7448	1.4341	1.0940	1.0266	0.9775
	$\overline{w^2}/(2 \times \text{TKE})$	0.2227	0.1599	0.1647	0.1303	0.1890	0.1408
3	TKE	0.4093	1.6368	1.0605	0.6001	0.7572	0.5590
	$\overline{w^2}/(2 \times \text{TKE})$	0.1181	0.0718	0.0793	0.0894	0.1344	0.1080

After FFP for the 2011 fire, temperatures near the canopy top (20 m AGL) dropped below the ambient temperature before FFP at that height by more than 5°C before returning to ambient-level temperatures 10–20 min after FFP (Fig. 3a). The temperature drop below ambient conditions was much less substantial at the 3- and 10-m levels, well within the interior of the overstory vegetation layer. No such temperature variation after FFP was observed for the lower-intensity 2012 fire (Fig. 3b). The temperature variations after FFP were consistent with the variations in vertical velocity that occurred. Downdrafts approaching -1 m s^{-1} near the canopy top occurred after FFP for the 2011 fire, which apparently brought cooler air from above into the canopy-top region (Fig. 3e); downdrafts following FFP for the 2012 fire were much less significant (Fig. 3f). TKE values after FFP during the 2011 fire generally decreased to values observed before FFP at all levels but showed considerable variability near the canopy top (Fig. 3g). The TKE values following FFP during the 2012 fire were very similar to the observed values before and during FFP (Fig. 3h).

The analyses of Heilman et al. (2015) also found the turbulence regimes during the two fire experiments to be highly anisotropic at large eddy sizes, with the horizontal component ($u^2 + v^2$) of the total TKE dominating over the vertical component (w^2) such that $\overline{w^2}/(2 \times \text{TKE}) < 0.33$, even during FFP periods when buoyancy was at a maximum and was conducive to large perturbations in vertical velocity. Table 1 contains a summary of the TKE and turbulence anisotropy [$\overline{w^2}/(2 \times \text{TKE})$] variations within defined 30-min-duration pre-FFP (1435–1505 EDT 20 March 2011; 1452–1522 EST 6 March 2012), FFP (1505–1535 EDT 20 March 2011; 1522–1552 EST 6 March 2012), and post-FFP (1535–1605 EDT 20 March 2011; 1552–1622 EST 6 March 2012) periods as discussed in Heilman et al. (2015).

To further understand how turbulence anisotropy in the fire environment can vary with local atmospheric stability, average $\overline{w^2}/(2 \times \text{TKE})$ values were computed

for different stability categories (zL^{-1}), where z is height (m) and L is the local Obukhov length. The results are shown in Fig. 4. During the 90-min fire period encompassing the defined pre-FFP, FFP, and post-FFP periods for both the 2011 and 2012 fire experiments, the most frequently occurring 1-min-averaged zL^{-1} values were between 0 and -0.25 . Instances of highly unstable conditions as noted by zL^{-1} values of less than -3 , although infrequent, did occur during the fire periods for both experiments. Average $\overline{w^2}/(2 \times \text{TKE})$ values within the $-0.25 < zL^{-1} < 0$ stability category were always less than 0.15 at all height levels for both experiments. The turbulence regimes tended to be less anisotropic [i.e., $\overline{w^2}/(2 \times \text{TKE})$ values closer to 0.33] as instability increased, although the coefficients of determination for the trends in the 2011 fire experiment were all less than 0.3 ($r^2 = 0.26$ at 3 m, 0.07 at 10 m, and 0.10 at 20 m). The trends were larger and more significant ($r^2 = 0.41$ at 3 m, 0.83 at 10 m, and 0.65 at 20 m) in the 2012 experiment.

b. TKE budget

The relative contributions of buoyancy production of turbulence energy, mechanical production of turbulence energy resulting from vertical shear in the horizontal winds, and vertical turbulent transport (diffusion) of turbulence energy to the local TKE tendencies during the 2011 and 2012 fire experiments are shown in Fig. 5. For the 2011 fire experiment, the contributions of buoyancy, shear, and diffusion to TKE tendencies were largest in the 10–20-m layer and were smallest in the 0–3-m layer (Figs. 5a,c,e) close to the time of FFP (1520 EDT). This is consistent with the vertical profile of TKE inferred from Fig. 3g and the region of enhanced potential wind shear associated with the relatively large gradient in plant-area density that characterized the 10–20-m layer (Fig. 1). The production of TKE by buoyancy was larger than the production resulting from vertical wind shear in the mid- to upper-canopy levels (10–20-m layer) as well as near the surface (0–3-m layer) around the time of FFP. Vertical turbulent diffusion tended to

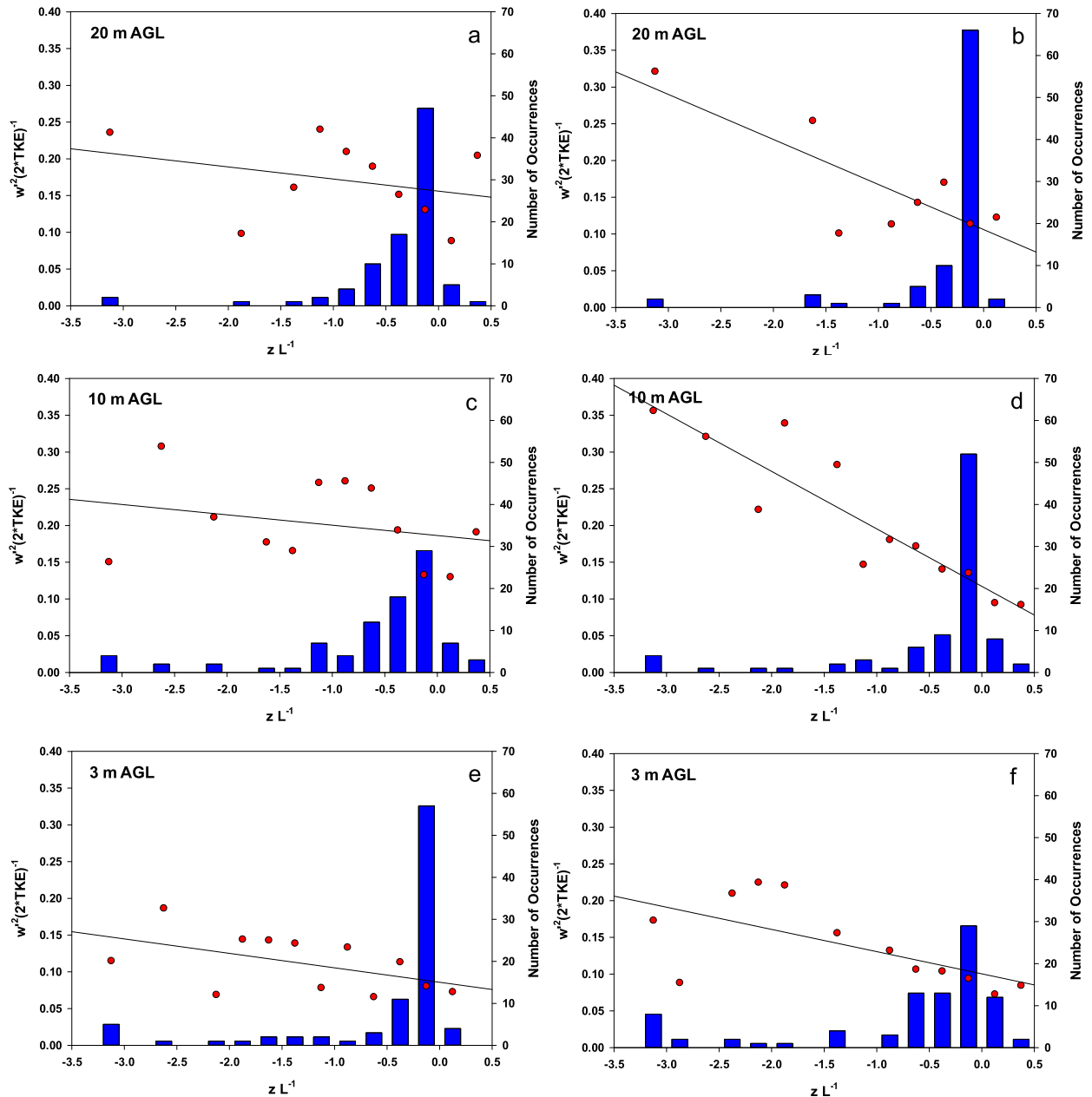


FIG. 4. Variation in anisotropy (red circles), expressed as 1-min-averaged $\overline{w^2}/(2 \times \text{TKE})$ values, under different stability categories (zL^{-1}), and the cumulative number of occurrences (bar chart) on which zL^{-1} values fell within each stability category during the pre-FFP, FFP, and post-FFP periods (total of 90 min) for the (left) 20 Mar 2011 experiment and (right) 6 Mar 2012 experiment at (a), (b) 20, (c), (d) 10, and (e), (f) 3 m AGL. An increment of 0.25 ($-0.25 < zL^{-1} < 0$, $-0.5 < zL^{-1} < 0.25$, etc.) was defined for each stability category. Linear regression lines are included to show overall relative increases in $\overline{w^2}/(2 \times \text{TKE})$ values as instability increased.

reduce TKE in all layers around the time of FFP, with maximum diffusion-value magnitudes exceeding both buoyancy and shear-production maximum magnitudes throughout the vertical extent of the overstory vegetation layer. Buoyancy and shear production of TKE and the vertical diffusion of TKE decreased rapidly in all layers after the FFP peak magnitudes were observed.

Following this period of rapid decreases in the production and diffusion of TKE, secondary peaks in shear production of TKE occurred in the 3–10- and 10–20-m layers. Within the 0–3-m layer, maximum shear production actually occurred about 11 min after FFP instead of during FFP. These peaks in shear production of TKE following FFP were associated with fire-induced

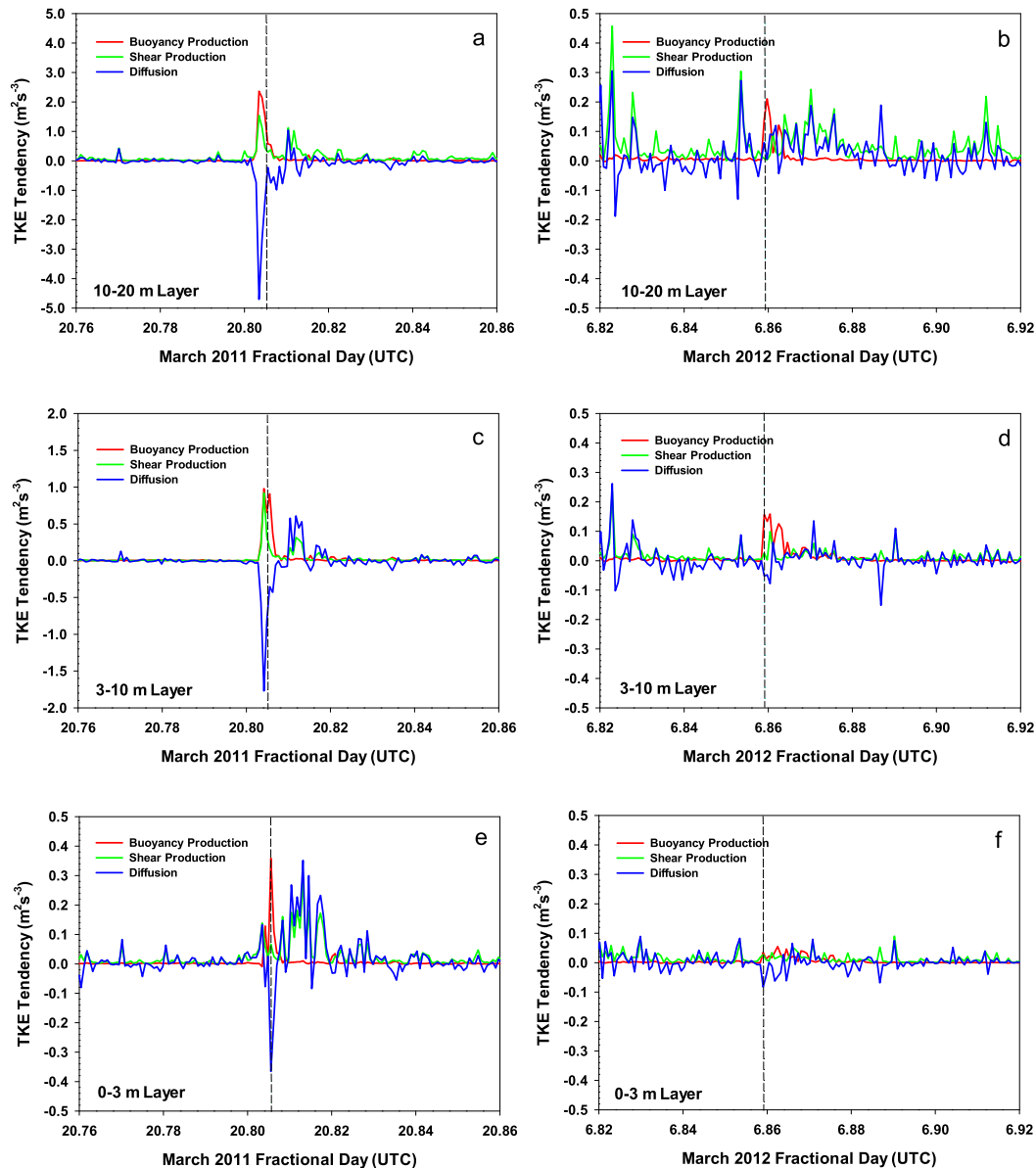


FIG. 5. Observed contributions of buoyancy, shear (vertical) production, and vertical turbulent transport (diffusion) to the TKE tendency in the (a),(b) 10–20-, (c),(d) 3–10-, and (e),(f) 0–3-m layers at the 20-m tower locations before, during, and after the (left) 20 Mar 2011 and (right) 6 Mar 2012 line fires passed the towers. Vertical dashed lines indicate times of fire-front passage. Note the differences in scale between the three layers for the TKE tendencies during the 20 Mar 2011 experiment.

horizontal inflow (and downdrafts) behind the eastward-spreading (backing) line fire (see Figs. 3c,e), which increased wind shears within the vegetation layer and contributed to the post-FFP increases in TKE that are shown in Fig. 3g.

During the lower-intensity 2012 fire experiment, vertical variations in the buoyancy and shear production of TKE and the vertical diffusion of TKE within the overstory vegetation layer (Figs. 5b,d,f) were much

smaller than the variations during the 2011 fire experiment. At the time of FFP, the maximum 1-min-averaged buoyancy production of TKE values in each layer was about an order of magnitude smaller than the corresponding values in the 2011 experiment. Peaks in shear production and diffusion at the time of FFP were also small or nonexistent in the 0–3-, 3–10-, and 10–20-m layers. Following FFP, the temporal variations in buoyancy and shear production of TKE and diffusion of

TABLE 2. Average buoyancy production B , shear production S , and diffusion D of TKE (m^2s^{-3}), before, during, and after FFP in the 10–20-, 3–10-, and 0–3-m layers as measured on the 20-m towers for the 20 Mar 2011 and 6 Mar 2012 prescribed fire experiments.

Layer	Quantity	20 Mar 2011 (EDT)			6 Mar 2012 (EST)		
		Before FFP (1415–1514)	During FFP (1515–1525)	After FFP (1526–1625)	Before FFP (1432–1531)	During FFP (1532–1542)	After FFP (1543–1642)
10–20	B	0.0068	0.7174	0.0228	0.0069	0.0667	0.0048
	S	0.0599	0.4337	0.1617	0.0524	0.0275	0.0540
	D	0.0069	−1.2097	−0.0114	0.0107	0.0341	0.0321
3–10	B	0.0041	0.3068	0.0123	0.0044	0.0654	0.0100
	S	0.0046	0.1687	0.0346	0.0205	0.0189	0.0137
	D	<0.0001	−0.3832	0.0367	0.0034	−0.0124	0.0073
0–3	B	0.0016	0.0617	0.0038	0.0017	0.0165	0.0068
	S	0.0102	0.0555	0.0398	0.0166	0.0131	0.0133
	D	0.0040	−0.0216	0.0416	0.0060	−0.0233	0.0011

TKE were similar to the variations observed prior to FFP.

A quantitative summary of the average buoyancy, shear, and diffusion effects on TKE tendencies before, during, and after FFP as shown in Fig. 5 can be found in Table 2. For this quantitative summary, averages were computed for the 1-h period ending 6 min before FFP (2011 experiment: 1415–1514 EDT; 2012 experiment: 1432–1531 EST), the 11-min period centered on the time of FFP (2011 experiment: 1515–1525 EDT; 2012 experiment: 1532–1542 EST), and the 1-h period beginning 6 min after FFP (2011 experiment: 1526–1625 EDT; 2012 experiment: 1543–1642 EST). The period averages shown in Table 2 indicate that vertical wind shear was a larger contributor to TKE production than buoyancy was in all layers before and after FFP, whereas during the defined short FFP periods buoyancy was a larger contributor than vertical wind shear. Period averages of the vertical diffusion of TKE in each layer were almost always positive (contributing to an increase in TKE) before and after FFP, except in the 10–20-m layer

following FFP for the 2011 experiment. During the FFP periods, vertical diffusion almost always tended to reduce TKE in each layer.

The TKE-budget averages in Table 2 and the computed ratios of average buoyancy, shear, and diffusion values between the 10–20-m layer and the 3–10- and 0–3-m layers that are shown in Table 3 highlight some of the impacts that forest overstory vegetation can have on the spatial variability in TKE-budget terms before, during, and after FFP. During the 20 March 2011 experiment, average TKE values at the 20-m level were about 3 times the values at the 10-m level and 4–5 times the values at the 3-m level during the entire pre-FFP–post-FFP period. The buoyancy-production ratios, on the other hand, were substantially larger during the FFP period than before or after FFP. During the FFP period, the shear-production ratio describing vertical variability over the mid- to upper portions of the forest overstory layer (S_{10-20}/S_{3-10}) was less than the corresponding ratios before and after FFP. The FFP period resulted in an increase in the S_{10-20}/S_{0-3} ratio relative to the pre- and

TABLE 3. Ratios of TKE at 20 m (TKE_{20}) to TKE at the 10-m (TKE_{10}) and 3-m (TKE_3) levels, respectively, and the associated ratios of buoyancy production, shear production, and diffusion in the 10–20-m layer (B_{10-20} , S_{10-20} , and D_{10-20}) to buoyancy production, shear production, and diffusion in the 3–10-m (B_{3-10} , S_{3-10} , and D_{3-10}) and 0–3-m (B_{0-3} , S_{0-3} , and D_{0-3}) layers, respectively, before, during, and after FFP at the 20-m towers for the 20 Mar 2011 and 6 Mar 2012 fire experiments.

Ratio	20 Mar 2011 (EDT)			6 Mar 2012 (EST)		
	Before FFP (1415–1514)	During FFP (1515–1525)	After FFP (1526–1625)	Before FFP (1432–1531)	During FFP (1532–1542)	After FFP (1543–1642)
$\text{TKE}_{20}/\text{TKE}_{10}$	3.35	3.09	2.99	2.09	1.58	2.66
B_{10-20}/B_{3-10}	1.66	2.34	1.85	1.57	1.02	0.48
S_{10-20}/S_{3-10}	13.02	2.57	4.67	2.56	1.46	3.94
D_{10-20}/D_{3-10}	286.16	3.16	−0.31	3.15	−2.75	4.40
$\text{TKE}_{20}/\text{TKE}_3$	4.92	5.61	4.60	3.82	2.01	4.42
B_{10-20}/B_{0-3}	4.25	11.63	6.00	4.06	4.04	0.71
S_{10-20}/S_{0-3}	5.87	7.81	4.06	3.16	2.10	4.06
D_{10-20}/D_{0-3}	1.73	56.00	−0.27	1.78	−1.46	29.18

post-FFP ratios, however. This result suggests that, relative to shear production in the upper-canopy layer (10–20 m), the fire tended to enhance shear production in the midcanopy (3–10 m) layer more than in the near-surface (0–3 m) layer. Diffusion ratios were both positive and negative and varied substantially from the pre-FFP period to the post-FFP period. Before FFP, the contribution of diffusion to TKE tendency in the midcanopy layer (3–10 m) was positive and minimal relative to the average positive diffusion contribution in the upper-canopy layer ($D_{3-10} < 0.0001 \text{ m}^2 \text{ s}^{-3}$, $D_{10-20} = 0.0069$, and $D_{10-20}/D_{3-10} = 286.16$). During the FFP period, however, it was the near-surface layer (0–3 m) that exhibited small (negative) contributions of diffusion to TKE tendency relative to the negative contributions in the upper-canopy layer ($D_{0-3} = -0.0216 \text{ m}^2 \text{ s}^{-3}$, $D_{10-20} = -1.2097$, and $D_{10-20}/D_{0-3} = 56.00$). After FFP, diffusion tended to decrease TKE values in the near-surface (0–3 m) and midcanopy (3–10 m) layers, and diffusion value magnitudes in those layers were substantially larger than the diffusion value in the 10–20-m layer ($D_{10-20}/D_{3-10} = -0.31$; $D_{10-20}/D_{0-3} = -0.27$).

During all periods for the lower-intensity 6 March 2012 fire experiment, TKE-value ratios between the 20-, 10-, and 3-m levels were smaller than during the 2011 experiment. During the FFP period, the lower-intensity line fire led to shear, buoyancy, and diffusion ratios (Table 3) that were less than what was observed during FFP for the 2011 experiment, an indication of less spatial variability in TKE-budget processes through the vertical extent of the forest overstory layer during the 2012 experiment. Unlike in the 2011 experiment, buoyancy-production ratios actually decreased from the pre-FFP period to the FFP period and on to the post-FFP period, and all shear-production ratios during the FFP period were smaller than the ratios before and after FFP.

A prominent feature in the TKE-budget time series shown in Fig. 5 is the concurrent peaks in shear production and diffusion of TKE following FFP in all layers, an indication that relatively high TKE from above the canopy was likely diffusing downward into the canopy layer and reinforcing the increase in TKE caused by shear production there. The relative strength of the positive correlations between vertical diffusion and vertical wind shear production of TKE in each layer following FFP is shown in Fig. 6. Correlations during this period following FFP were strongest in the 0–3-m layer ($r^2 = 0.92$) and weakest in the 10–20-m layer ($r^2 = 0.48$). The regression-line slopes shown in Fig. 6 indicate that the relative increases in diffusion of TKE when compared with increases in shear production were largest in the 3–10-m layer during this period. Table 4 provides a comparison of the correlations and slope values for

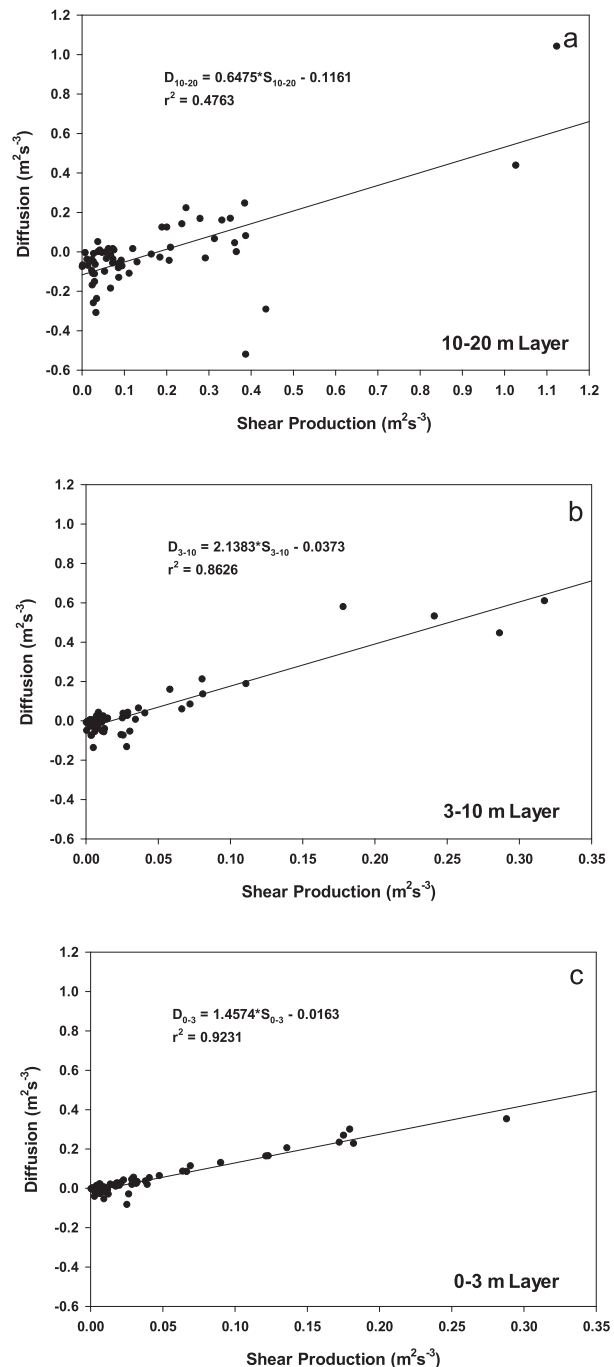


FIG. 6. Observed 1-min-averaged vertical diffusion of TKE as a function of the 1-min-averaged vertical shear production of TKE in the (a) 10–20-m layer (D_{10-20} vs S_{10-20}), (b) 3–10-m layer (D_{3-10} vs S_{3-10}), and (c) 0–3-m layer (D_{0-3} vs S_{0-3}) during the 1-h period beginning 6 min after FFP (1526–1625 EDT) at the 20-m tower location for the 20 Mar 2011 fire experiment. Linear regressions (solid lines) of the diffusion vs shear observations along with regression equations and coefficients of determination r^2 are included in each panel.

TABLE 4. Slope and r^2 values of the linear-regression lines characterizing the plots of vertical diffusion of TKE vs vertical wind shear production of TKE before and after FFP in the 10–20-, 3–10-, and 0–3-m layers during the 20 Mar 2011 and 6 Mar 2012 fire experiments.

Layer	20 Mar 2011 (EDT)				6 Mar 2012 (EST)			
	Before FFP (1415–1514)		After FFP (1526–1625)		Before FFP (1432–1531)		After FFP (1543–1642)	
	Slope	r^2	Slope	r^2	Slope	r^2	Slope	r^2
10–20	0.71	0.57	0.65	0.48	0.73	0.47	0.83	0.56
3–10	2.18	0.40	2.14	0.86	1.33	0.66	1.17	0.31
0–3	1.01	0.28	1.46	0.92	1.18	0.44	0.57	0.15

diffusion versus shear production during this post-FFP period with the correlations and slope values that characterized the pre-FFP period. In contrast to what occurred after FFP, the positive correlations for diffusion versus shear production were generally smaller and decreased from the 10–20-m layer ($r^2 = 0.57$) down to the 0–3-m layer ($r^2 = 0.28$) during the 1-h period leading up to the time of FFP. The regression slope values were largest in the 3–10-m layer during both periods, however, and the positive correlations before and after FFP are in stark contrast to what occurred around the time of FFP when diffusion tended to decrease TKE values in all layers (Figs. 5a,c,e).

The strong correlation between diffusion and shear production observed after FFP in the 0–3-m layer during the 2011 higher-intensity fire experiment ($r^2 = 0.92$) was absent during the 2012 lower-intensity fire experiment ($r^2 = 0.15$). Post-FFP correlations for diffusion versus shear production increased from the 0–3-m layer up to the 10–20-m layer for the 2012 experiment, although they were relatively weak, again in contrast to the 2011 experiment.

c. Velocity-distribution skewness

Previous studies have shown that turbulence regimes inside forest vegetation layers can be highly non-Gaussian, with horizontal and vertical wind distributions often exhibiting skewness values on the order of +1 and –1, respectively (Baldocchi and Meyers 1989; Amiro 1990; Leclerc et al. 1991). The observed horizontal and vertical velocities before, during, and after FFP for both fire experiments (Figs. 3c–f) were further examined for skewness to assess how the presence of surface fires can potentially alter the skewness in the horizontal and vertical wind fields that are typically observed during daytime convective conditions inside forest vegetation layers. For this analysis, Sk_u , Sk_v , and Sk_w values were computed over the same 1-h, 11-min, and 1-h periods before, during, and after FFP, respectively, that were used for the turbulence-budget analyses.

As shown in Fig. 7, vertical velocity skewness before FFP for both fire experiments was negative and was generally consistent with past nonfire observational studies in forested environments (e.g., Amiro 1990); maximum negative skewness occurred near the surface ($Sk_w = -0.43$ at 3 m during the 2012 experiment) or at midcanopy levels ($Sk_w = -0.37$ at 10 m during the 2011 experiment). The advancing line fires during the FFP

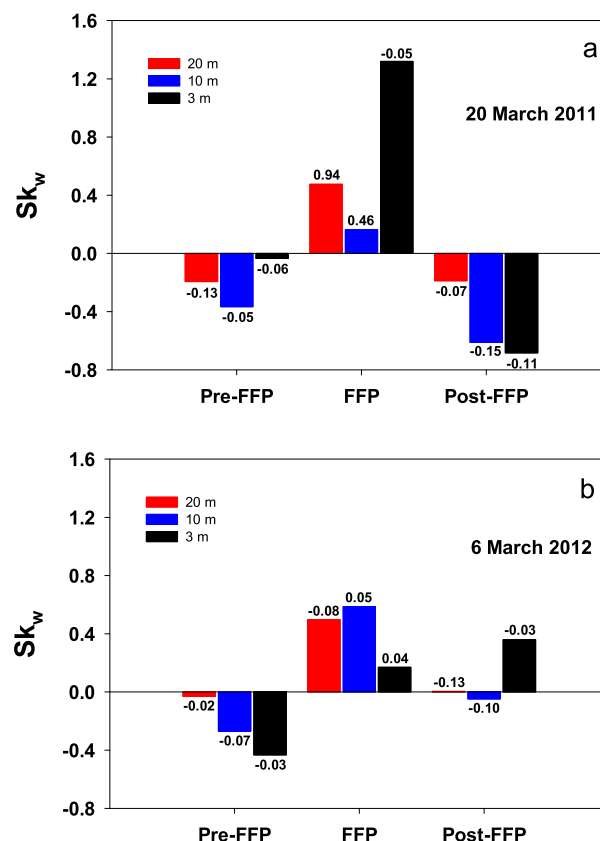


FIG. 7. Skewness Sk_w in the vertical velocity distributions at the 20-, 10-, and 3-m levels before, during, and after FFP at the 20-m towers for the (a) 20 Mar 2011 and (b) 6 Mar 2012 fire experiments. The number above or below each bar indicates the average vertical wind speed (m s^{-1}) at that level during the designated period.

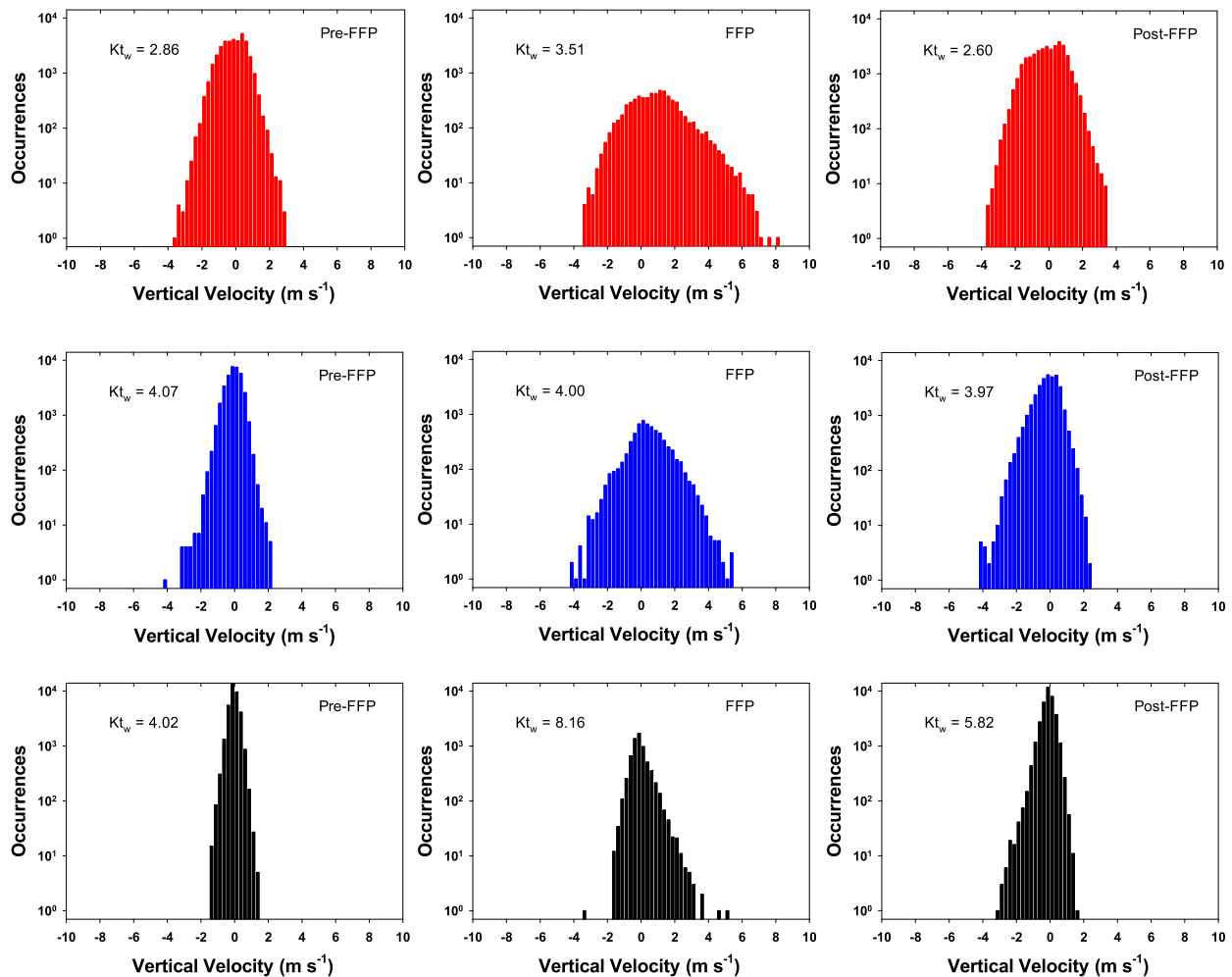


FIG. 8. Vertical velocity distributions (0.25 m s^{-1} increments) as based on 10-Hz sonic-anemometer measurements at (top) 20, (middle) 10, and (bottom) 3 m AGL (left) before FFP, (center) during FFP, and (right) after FFP at the 20-m tower location for the 20 Mar 2011 fire experiment. Kurtosis values Kt_w associated with the distributions are included in each panel.

periods for both experiments generated positively skewed vertical velocity distributions at all height levels. During the 2011 experiment (Fig. 7a) the skewness of the vertical velocity distribution reached 1.32 at the 3-m level, whereas during the 2012 experiment (Fig. 7b) maximum positive skewness occurred at the 10-m level ($Sk_w = 0.59$). The two fire experiments resulted in very different vertical velocity distributions during the post-FFP periods. For the higher-intensity 2011 fire experiment, vertical turbulence was highly non-Gaussian at the 3-m ($Sk_w = -0.68$) and 10-m ($Sk_w = -0.61$) levels. Vertical turbulence during the lower-intensity 2012 fire experiment was more Gaussian in nature, with Sk_w magnitudes equal to 0.36 at the 3-m level and less than 0.05 at the 10- and 20-m levels.

The underlying height-dependent vertical velocity distributions (10-Hz data) associated with the 2011

fire-experiment skewness values plotted in Fig. 7a are shown in Fig. 8 to highlight the actual spread in vertical velocities that characterized the periods before, during, and after FFP. A general feature of the distributions during all three periods is a flattening and spreading of the distributions as one moves upward from the 3-m level to the 20-m level, which is consistent with increasing TKE values (and increasing values in the vertical component of $TKE w^2$) from the 3-m level to the 20-m level (Fig. 3g). At the 20-m level during the pre-FFP period, maximum downdraft and updraft speeds recorded were -3.5 and 3.0 m s^{-1} , respectively. During the post-FFP period those values were -3.7 and 3.5 m s^{-1} , respectively. At the 3-m level, maximum downdraft and updraft magnitudes were less than 1.5 m s^{-1} during the pre-FFP period and less than 3.2 m s^{-1} during the post-FFP period. During the FFP period the variability in distributions at the different

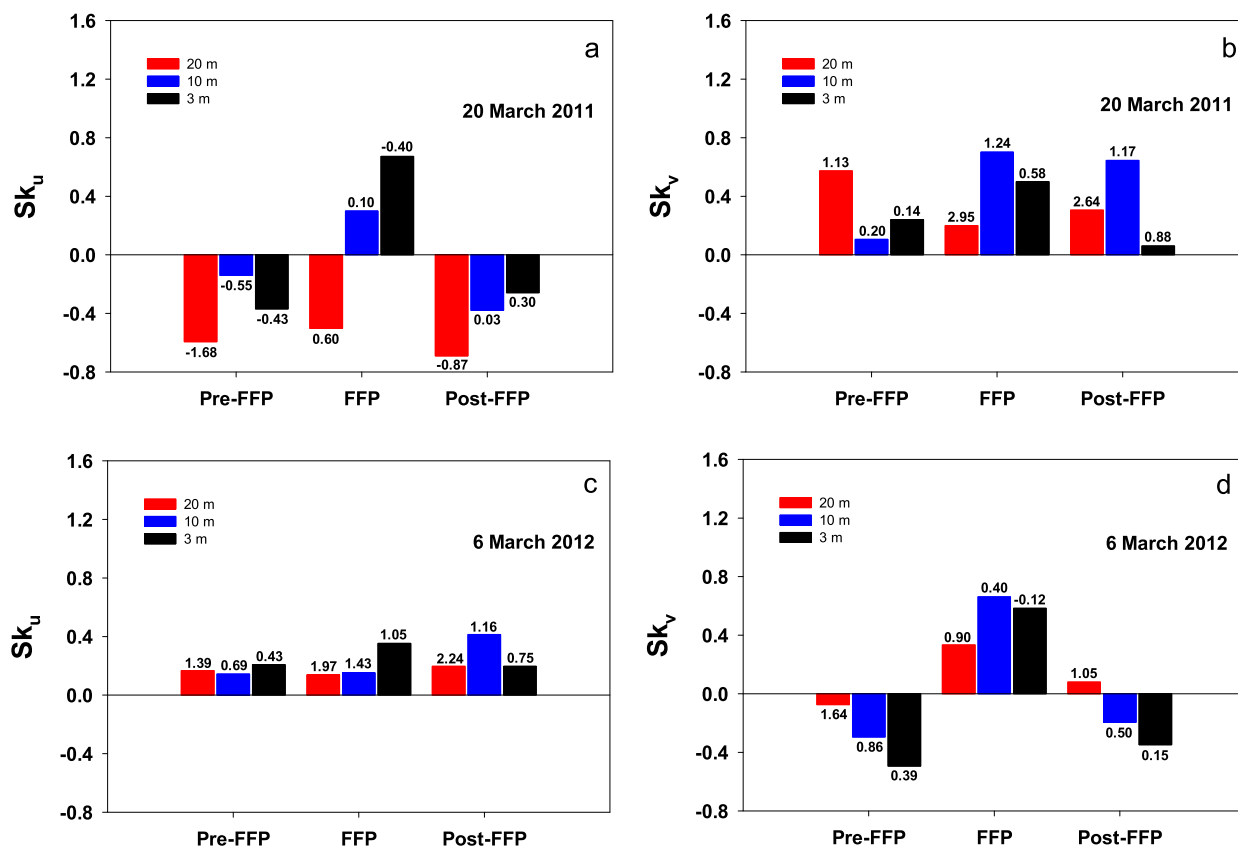


FIG. 9. Skewness in the (left) U and (right) V velocity distributions at the 20-, 10-, and 3-m levels before, during, and after FFP at the 20-m towers for the (a),(b) 20 Mar 2011 and (c),(d) 6 Mar 2012 fire experiments. The number above or below each bar indicates the average U or V wind speed (m s^{-1}) at that level during the designated period.

height levels was most pronounced. At the 20-m level, the maximum recorded downdraft and updraft speeds were -3.5 and 8.2 m s^{-1} , respectively. At the 3-m level, the maximum downdraft and updraft speeds were -3.3 m s^{-1} and 5.2 m s^{-1} , respectively. In comparing the pre-FFP distributions with the post-FFP distributions at all levels, there is seen also a general flattening and spreading of the distributions in the post-FFP environment.

The horizontal (zonal and meridional) velocity distributions also exhibited substantial skewness (Fig. 9). For the 2011 experiment (Figs. 9a,b), the prevailing southeasterly winds (negative U and positive V) at the burn site were associated with negatively skewed U and positively skewed V velocity distributions at all levels and during all periods, except for the 3- and 10-m levels during the FFP period when mean horizontal winds shifted to southwesterly (positive U and positive V) at the 10- and 20-m levels. During the post-FFP period, mean horizontal winds were predominantly southerly to southwesterly at the 10- and 3-m levels, with 20-m-level mean winds returning to southeasterly. Similar to the

findings of Amiro (1990), the skewness magnitudes for the horizontal velocity component distributions tended to be largest at mid- to upper-canopy levels during the pre- and post-FFP periods, unlike the skewness values for the vertical velocity distribution, which tended to maximize in the lower portion of the vegetation layer. For the 2012 experiment, the largest skewness magnitudes were associated with the V velocity distributions (Figs. 9c,d). Furthermore, the westward-spreading line fires against the predominately southwesterly winds had a much more substantial effect on the skewness values of the V velocity distribution; Sk_v values were negative during the pre and post-FFP periods but were positive during the FFP period.

4. Summary and conclusions

In this study, we expanded upon the Heilman et al. (2015) initial analysis of turbulence regimes that occurred during two low-intensity prescribed fires conducted in the New Jersey Pine Barrens in 2011 and 2012. Our primary focus for this study was an examination of

the effects of spreading surface line fires typical of prescribed fires conducted in forested areas of the northeastern United States on 1) local stability and turbulence anisotropy relationships; 2) three important processes that affect turbulent energy evolution inside forest canopies, namely production of turbulent energy due to vertical wind shears, the production of turbulent energy due to buoyancy, and the vertical turbulent transport or diffusion of turbulent energy; and 3) the skewness of horizontal and vertical velocity distributions that characterizes flow through forest canopies.

As reported in [Heilman et al. \(2015\)](#), the largest TKE values before, during, and after FFP in both experiments occurred near the canopy top, with the largest increases in TKE during FFP also occurring near the canopy top for the higher-intensity 2011 fire. Turbulence regimes were anisotropic, particularly at large eddy sizes, at all levels within the forest overstory vegetation layer before, during, and after FFP, with the vertical component of TKE usually making up less than 25% of the total TKE. The enhanced heating inside the forest vegetation layers that occurred in the vicinity of the line fires led to a wide range of stability conditions, as quantified by computed zL^{-1} values at different heights within the vegetation layers, with turbulence anisotropy generally decreasing with increasing instability. Occurrences of $-0.25 < zL^{-1} < 0$ were most common during the 90-min periods centered on the times of FFP for the two experiments, and the average vertical-component proportion of the total TKE in that stability category was less than 0.15 at all height levels. Highly unstable conditions characterized by zL^{-1} values of less than -3.0 also occurred sporadically during these periods at all levels for both experiments. The average vertical-component proportion of the total TKE during these sporadic highly unstable conditions was still usually less than 0.33, an indication that horizontal velocity perturbations can be more significant than vertical velocity perturbations even during FFP episodes.

For the higher-intensity 2011 fire experiment, turbulence energy production from vertical wind shear and buoyancy increased significantly during FFP periods, especially in the upper portions of the canopy layer. Vertical diffusion of turbulence energy also increased significantly during the FFP periods, was largest in the upper portions of the canopy layer, and acted to decrease turbulence energy at all levels. Buoyancy, vertical wind shear, and diffusion effects on the evolution of turbulence energy were much smaller during the lower-intensity 2012 fire experiment. For both experiments, the production of turbulence energy caused by vertical wind shear almost always exceeded the buoyancy production of energy at all levels within the overstory

vegetation layer during the periods before and after FFP, whereas diffusion tended to increase turbulence energy at all levels before and after FFP. The results also suggest that sufficiently intense surface line fires at the time of FFP can increase shear production of turbulence energy at the midcanopy level more than near the surface, relative to shear production in the upper portions of the canopy.

Diffusion of turbulence energy was found to be positively correlated with shear production of turbulence energy in both the pre- and post-FFP environments, and the relative increases in turbulence energy diffusion when compared with increases in shear production were largest at midcanopy levels before and after FFP. Correlations between diffusion and shear production were notably stronger after FFP, however. Correlations also increased in moving from the upper portions of the canopy down to the near-surface layer in the post-FFP environment, in contrast to the pre-FFP environment in which correlations increased from the near-surface layer to the upper portions of the canopy. These spatial and temporal variations in correlations between diffusion and shear production indicate that the pre- and post-FFP environments where forest overstory vegetation is present can be very different with respect to how diffusion and shear production concurrently affect the evolution of turbulence energy within the canopy layer.

As noted in [section 2](#), the turbulence-budget analysis in this study was limited to buoyancy, vertical wind shear, and vertical diffusion effects because the monitoring network set up for the fire experiments was not sufficient to calculate all of the TKE-budget terms. On the basis of the time series of the 10-Hz wind data collected during the fire experiments along with the observed line-fire-spread rates and computed Reynolds stress and TKE values, the production of TKE by horizontal wind shears and the horizontal diffusion of TKE in the fire environment were of the same orders of magnitude as the production from vertical wind shears and the vertical diffusion of TKE, respectively. More-extensive monitoring networks like those planned for upcoming wildland fire experiments as part of the U.S. Department of Defense–Strategic Environmental Research and Development Program (SERDP) and the U.S. Joint Fire Science Program–Fire and Smoke Model Evaluation Experiment (FASMEE) are needed to generate higher-spatial-resolution turbulence datasets that are appropriate for accurately assessing TKE budgets in fire environments. The turbulence data collected from these experiments are also critical for evaluating coupled atmosphere–fire modeling systems that predict turbulence energy evolution and its impact on fire behavior and smoke dispersion.

Analyses in this study also suggest that spreading line fires can affect the skewness of the daytime horizontal and vertical velocity distributions that are typically observed inside forest vegetation layers. In particular, daytime vertical velocity distributions that tend to be highly negatively skewed inside forest vegetation layers (Sk_w of approximately -1 ; Amiro 1990) can become highly positively skewed ($Sk_w > 1$) during FFP periods and then become even more negatively skewed following FFP than the negatively skewed distributions that characterize the pre-FFP environment. The skewness variations that can occur from the pre-FFP period through the post-FFP period during fire events within forest vegetation layers are an important consideration in the application of operational prediction tools for local smoke dispersion. Many of those tools either assume constant Gaussian turbulence regimes (minimal velocity skewness) for diffusing fire emissions [e.g., “VSMOKE”: Lavdas 1996; the Simple Approach Smoke Estimation Model (SASEM): Riebau et al. 1988] or include dispersion parameterizations that only account for non-Gaussian turbulence associated with positively skewed vertical velocity distributions typical of daytime convective boundary layers (Sk_w of 0.2–0.8; Wyngaard 1988; Lenschow and Stephens 1980; LeMone 1990) (e.g., CALPUFF: Scire et al. 2000; FLEXPART: Stohl et al. 2005; Brioude et al. 2013).

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REFERENCES

- Albini, F. A., and R. G. Baughman, 1979: Estimating windspeeds for predicting wildland fire behavior. USDA Forest Service Research Paper INT-221, 24 pp., <https://ia801001.us.archive.org/22/items/estimatingwindsp221albi/estimatingwindsp221albi.pdf>.
- Alexander, M. E., 1982: Calculating and interpreting forest fire intensities. *Can. J. Bot.*, **60**, 349–357, doi:10.1139/b82-048.
- Amiro, B. D., 1990: Comparison of turbulence statistics within three boreal forest canopies. *Bound.-Layer Meteor.*, **51**, 99–121, doi:10.1007/BF00120463.
- Baldocchi, D. D., and T. P. Meyers, 1989: The effects of extreme turbulent events on the estimation of aerodynamic variables in a deciduous forest canopy. *Agric. For. Meteorol.*, **48**, 117–134, doi:10.1016/0168-1923(89)90011-7.
- , and K. B. Wilson, 2001: Modeling CO₂ and water vapor exchange of a temperate broadleaved forest across hourly to decadal time scales. *Ecol. Modell.*, **142**, 155–184, doi:10.1016/S0304-3800(01)00287-3.
- Brioude, J., and Coauthors, 2013: The Lagrangian particle dispersion model FLEXPART-WRF version 3.1. *Geosci. Model Dev.*, **6**, 1889–1904, doi:10.5194/gmd-6-1889-2013.
- Byram, G. M., 1959: Combustion of forest fuels. *Forest Fire: Control and Use*, 1st ed. K. P. Davis, Ed., McGraw-Hill, 61–89.
- Charland, A. M., and C. B. Clements, 2013: Kinematic structure of a wildland fire plume observed by Doppler lidar. *J. Geophys. Res. Atmos.*, **118**, 3200–3212, doi:10.1002/jgrd.50308.
- Clements, C. B., and Coauthors, 2007: Observing the dynamics of wildland grass fires: FireFlux—A field validation experiment. *Bull. Amer. Meteor. Soc.*, **88**, 1369–1382, doi:10.1175/BAMS-88-9-1369.
- , S. Zhong, X. Bian, W. E. Heilman, and D. W. Byun, 2008: First observations of turbulence generated by grass fires. *J. Geophys. Res.*, **113**, D22102, doi:10.1029/2008JD010014.
- , and Coauthors, 2016: Fire weather conditions and fire-atmosphere interactions observed during low-intensity prescribed fires—RxCADRE 2012. *Int. J. Wildland Fire*, **25**, 90–101, doi:10.1071/WF14173.
- Dupont, S., and Y. Brunet, 2008: Influence of foliar density profile on canopy flow: A large-eddy simulation study. *Agric. For. Meteorol.*, **148**, 976–990, doi:10.1016/j.agrformet.2008.01.014.
- Erisman, J. W., and G. Draaijers, 2003: Deposition to forests in Europe: Most important factors influencing dry deposition and models used for generalization. *Environ. Pollut.*, **124**, 379–388, doi:10.1016/S0269-7491(03)00049-6.
- Finnigan, J., 2000: Turbulence in plant canopies. *Annu. Rev. Fluid Mech.*, **32**, 519–571, doi:10.1146/annurev.fluid.32.1.519.
- Flesch, T. K., and J. D. Wilson, 1992: A two-dimensional trajectory-simulation model for non-Gaussian, inhomogeneous turbulence within plant canopies. *Bound.-Layer Meteorol.*, **61**, 349–374, doi:10.1007/BF00119097.
- Heilman, W. E., and Coauthors, 2013: Development of modeling tools for predicting smoke dispersion from low-intensity fires. U.S. Joint Fire Science Program Final Rep. 09-1-04-1, 64 pp., https://www.fire-science.gov/projects/09-1-04-1/project/09-1-04-1_final_report.pdf.
- , C. B. Clements, D. Seto, X. Bian, K. L. Clark, N. S. Skowronski, and J. L. Hom, 2015: Observations of fire-induced turbulence regimes during low-intensity wildland fires in forested environments: Implications for smoke dispersion. *Atmos. Sci. Lett.*, **16**, 453–460, doi:10.1002/asl.581.
- Kiefer, M. T., S. Zhong, W. E. Heilman, J. J. Charney, and X. Bian, 2013: Evaluation of an ARPS-based canopy flow modeling system for use in future operational smoke prediction efforts. *J. Geophys. Res. Atmos.*, **118**, 6175–6188, doi:10.1002/jgrd.50491.
- , and Coauthors, 2014: Multiscale simulation of a prescribed fire event in the New Jersey Pine Barrens using ARPS-CANOPY. *J. Appl. Meteor. Climatol.*, **53**, 793–812, doi:10.1175/JAMC-D-13-0131.1.
- Larkin, N. K., and Coauthors, 2009: The BlueSky smoke modeling framework. *Int. J. Wildland Fire*, **18**, 906–920, doi:10.1071/WF07086.
- Lavdas, L. G., 1996: Program VSMOKE—User’s manual. USDA Forest Service Southeastern Forest Experiment Station Tech. Rep. SRS-6, 156 pp., <https://doi.org/10.2737/SRS-GTR-006>.
- Leclerc, M. Y., K. C. Beissner, R. H. Shaw, G. den Hartog, and H. H. Neumann, 1991: The influence of buoyancy on third-order turbulent velocity statistics within a deciduous forest. *Bound.-Layer Meteorol.*, **55**, 109–123, doi:10.1007/BF00119329.
- LeMone, M. A., 1990: Some observations of vertical velocity skewness in the convective planetary boundary layer. *J. Atmos. Sci.*, **47**, 1163–1169, doi:10.1175/1520-0469(1990)047<1163:SOOVVS>2.0.CO;2.
- Lenschow, D. H., and P. L. Stephens, 1980: The role of thermals in the convective boundary layer. *Bound.-Layer Meteorol.*, **19**, 509–532, doi:10.1007/BF00122351.
- Nathan, R., G. G. Katul, B. Bohrer, A. Kuparinen, M. B. Soons, S. E. Thompson, A. Trakhtenbrot, and H. S. Horn, 2011:

- Mechanistic models of seed dispersal by wind. *Theor. Ecol.*, **4**, 113–132, doi:10.1007/s12080-011-0115-3.
- Ottmar, R. D., and Coauthors, 2016: Measurements, datasets and preliminary results from the RxCADRE project—2008, 2011 and 2012. *Int. J. Wildland Fire*, **25**, 1–9, doi:10.1071/WF14161.
- Raupach, M. R., and A. S. Thom, 1981: Turbulence in and above plant canopies. *Annu. Rev. Fluid Mech.*, **13**, 97–129, doi:10.1146/annurev.fl.13.010181.000525.
- Riebau, A. R., D. G. Fox, M. L. Sestak, B. Dailey, and S. F. Archer, 1988: Simple Approach Smoke Estimation Model. *Atmos. Environ.*, **22**, 783–788, doi:10.1016/0004-6981(88)90017-0.
- Ryan, K. C., 2002: Dynamic interactions between forest structure and fire behavior in boreal ecosystems. *Silva Fenn.*, **36**, 13–39, doi:10.14214/sf.548.
- Scire, J. G., D. G. Strimaitis, and R. J. Yamartino, 2000: A user's guide for the CALPUFF dispersion model (version 5). Earth Tech, Inc., Tech. Doc., 521 pp., http://www.src.com/calpuff/download/CALPUFF_UsersGuide.pdf.
- Seto, D., and C. B. Clements, 2011: Fire whirl evolution observed during a valley wind-sea breeze reversal. *J. Combust.*, **2011**, 569475, doi:10.1155/2011/569475.
- , —, and W. E. Heilman, 2013: Turbulence spectra measured during fire front passage. *Agric. For. Meteorol.*, **169**, 195–210, doi:10.1016/j.agrformet.2012.09.015.
- , T. M. Strand, C. B. Clements, H. Thistle, and R. Mickler, 2014: Wind and plume thermodynamic structures during low-intensity subcanopy fires. *Agric. For. Meteorol.*, **198–199**, 53–61, doi:10.1016/j.agrformet.2014.07.006.
- Skowronski, N., K. Clark, R. Nelson, J. Hom, and M. Patterson, 2007: Remotely sensed measurements of forest structure and fuel loads in the pinelands of New Jersey. *Remote Sens. Environ.*, **108**, 123–129, doi:10.1016/j.rse.2006.09.032.
- , —, M. Duveneck, and J. Hom, 2011: Three-dimensional canopy fuel loading predicted using upward and downward sensing lidar systems. *Remote Sens. Environ.*, **115**, 703–714, doi:10.1016/j.rse.2010.10.012.
- Smith, D. W., and T. D. James, 1978: Characteristics of prescribed burns and resultant short-term environmental changes in *Populus tremuloides* woodland in southern Ontario. *Can. J. Bot.*, **56**, 1782–1791, doi:10.1139/b78-213.
- Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa, 2005: Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2. *Atmos. Chem. Phys.*, **5**, 2461–2474, doi:10.5194/acp-5-2461-2005.
- Strand, T. M., and Coauthors, 2013: Sub-canopy transport and dispersion of smoke: A unique observation dataset and model evaluation. U.S. Joint Fire Science Program Final Rep. 09-1-04-2, 63 pp., https://www.fire.science.gov/projects/09-1-04-2/project/09-1-04-2_final_report.pdf.
- Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic, 666 pp.
- Su, H.-B., H. P. Schmid, C. S. Vogel, and P. S. Curtis, 2008: Effects of canopy morphology and thermal stability on mean flow and turbulence statistics observed inside a mixed hardwood forest. *Agric. For. Meteorol.*, **148**, 862–882, doi:10.1016/j.agrformet.2007.12.002.
- Sun, X. M., Z. L. Zhu, X. F. Wen, G. F. Yuan, and G. R. Yu, 2006: The impact of averaging period on eddy fluxes observed at ChinaFLUX sites. *Agric. For. Meteorol.*, **137**, 188–193, doi:10.1016/j.agrformet.2006.02.012.
- Taylor, S. W., B. M. Wotton, M. E. Alexander, and G. N. Dalrymple, 2004: Variation in wind and crown fire behaviour in a northern jack pine–black spruce forest. *Can. J. For. Res.*, **34**, 1561–1576, doi:10.1139/x04-116.
- Vickers, D., and C. K. Thomas, 2013: Some aspects of the turbulence kinetic energy and fluxes above and beneath a tall open pine forest canopy. *Agric. For. Meteorol.*, **181**, 143–151, doi:10.1016/j.agrformet.2013.07.014.
- Wilczak, J. M., S. P. Oncley, and S. A. Stage, 2001: Sonic anemometer tilt correction algorithms. *Bound.-Layer Meteorol.*, **99**, 127–150, doi:10.1023/A:1018966204465.
- Wilson, N. R., and R. H. Shaw, 1977: A higher order closure model for canopy flow. *J. Appl. Meteorol.*, **16**, 1197–1205, doi:10.1175/1520-0450(1977)016<1197:AHOCMF>2.0.CO;2.
- Wyngaard, J. C., 1988: Structure of the PBL. *Lectures on Air Pollution Modeling*, A. Venkatram and J. C. Wyngaard, Eds., Amer. Meteor. Soc., 9–61.