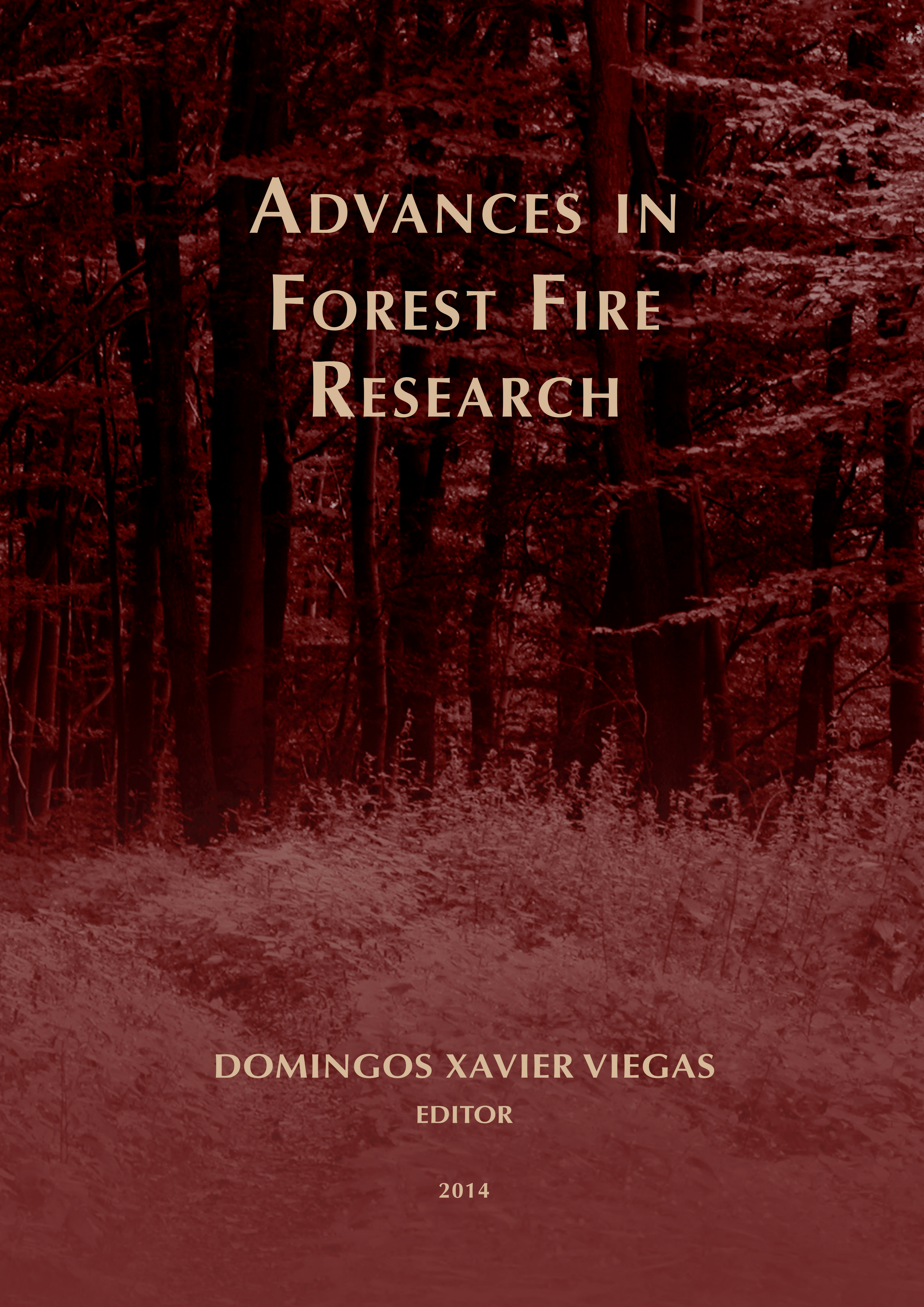

ADVANCES IN FOREST FIRE RESEARCH

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Turbulence structures observed during experimental fires in forest and grassland environments

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Abstract

Fire-atmosphere interactions can occur at spatial scales on the order of tens of meters at the fire front and to kilometers in plumes during large fires. However, few studies have focused on the observed turbulence structure in the immediate environment of propagating fires to further understand the relative importance of ambient and fire-induced turbulence on fire front propagation. In this study, turbulence structures during the passage of fire fronts were investigated using the data obtained from two field experiments. One fire was conducted over grass fuel under strong ambient mean winds and the other conducted in a forest sub-canopy environment under light ambient winds. The main objective of this research is to investigate scale-averaged variances over different fuels before, during, and after the fire front passage in relation to different fire intensities and atmospheric conditions. Time series data from in-situ sonic anemometer arrays are analyzed using wavelet signal processing to treat non-stationary process of the fire front passage. Only a small increase in u variance over the 2-4 s band was found during the fire front passage in the grass fire environment under the strong mean winds. The variance associated with low intensity sub-canopy fire was found to increase over 2-4 s and 8-16 s bands, due to intermittent convective smoke plume pulses of the low intensity sub-canopy fire.

Keywords: *Fire-induced wind, Fire-atmosphere interaction, Grass fire, Sub-canopy fire*

1. Introduction

Turbulent kinetic energy (TKE) is produced in the energy containing range and transported from large to small scales without the energy production or dissipation in the inertial subrange, and it is eventually converted to internal energy in the dissipation range. Turbulent eddy motion in these three regions is well recognized in the atmospheric boundary layer. However, because dynamical coupling of the wildfire and atmosphere (Clark *et al*. 1996) may occur over a very wide range of length and time scales depending upon fire intensity and the atmospheric conditions, it is questionable whether the traditional turbulence theory holds in wildfire environments where the atmosphere becomes highly unstable given extremely high flame temperatures and large sensible heat flux, particularly near the surface.

Sun *et al*. (2009) showed that a strong downdraft caused by an interaction between the fire-induced plume circulation and a strong eddy circulation in the ABL can bring down higher momentum from aloft to the surface and increase the rate of fire spread, especially for a large fire. Downdrafts have been observed during fast spreading grassfires (Clements *et al*. 2007). Seto *et al*. (2014) showed that despite lower plume temperatures low-intensity sub-canopy fires may potentially be able to generate nearly as strong fire-induced winds as wind-driven grass fires under favorable fuel conditions due to strong coupling between fire and atmosphere.

Initial analyses of turbulence spectra during fire front passage revealed that fire can influence the energy of the flow and turbulence over a wide frequency range (Seto *et al*. 2013). Although four datasets that were representative of various fuels and terrain were analyzed in the study, more experimental datasets are now available with better horizontal and vertical coverage of turbulence measurements. Additionally, the study only addressed qualitative aspect of the spectral energy in the spectral regions, and further investigation of TKE generation and dissipation processes during fire events are essential to corroborate the previous findings.

This paper examines the turbulence structures in fire environments during grass fire and sub-canopy fire experiments.

2. Experimental designs

FireFlux II, a comprehensive grassfire experiment, was conducted on 30 January 2013 at the University of Houston Coastal Center in Texas, USA and was designed with a head fire being allowed to burn directly underneath a 42-m and three 10-m micrometeorological towers (Figure 2). The fuels consist of a mixture of native grasses, including big bluestem (Andropogon gerardi), little bluestem (Schizachyrium scoparium), and long spike tridens (Tridens strictus). Each tower was equipped with multiple 3D sonic anemometers (20 m, 10 m, and 6 m AGL. The experiment was carried out with a head fire ignition under red flag warning conditions (Clements *et al*. this issue).

Three low-intensity prescribed burns were conducted during the late winter and early spring (February and March) of 2010 and 2011 at The Nature Conservancy's (TNC) Calloway Forest/Sandhills Preserve in North Carolina, USA (Figure 1). A majority of the surface fuels were in the 1-hr (defined as ¼ of an inch or less in diameter) size classification and consisted of long leaf pine litter, both cured and live wiregrass (*Aristida stricta*), American turkey oak (*Quercus laevis*), and regeneration long leaf pine. The mean tree height (h_c) was 20 m. The soil was sandy with little to no organic matter beyond the surface duff layer. In this study, turbulence data collected at a 20-m in-situ tower in 2011 was used for the analysis. The tower was equipped with multiple 3D sonic anemometers at 20 m, 10 m, and 3 m AGL. Backing and strip fire ignitions were employed during the experiment although blackline and strip head fire were also ignited around the tower. Fire propagation was limited to ground fuels. Hereafter, the two experiments discussed above are mentioned as FF2 and NC.

3. Data Processing

Streamwise and vertical velocity wavelet power spectra were computed using a continuous wavelet transform (complex Morlet) following Torrence and Compo (1998). Wavelet transforms are mathematical techniques based on group theory and square integrable representation and they use an analysing function called wavelets, which are localized in space, to decompose signals into space and scale (see Farge, 1992 for details). To examine fluctuations in local power over a range of scales, time series of scale-averaged wavelet power is presented in this study. Three wavelet scales were selected: 2-4 s, 8-16 s, and 32-64 s periods. The velocity data were averaged over 1 s before calculating the wavelet power.

4. Data Analysis and Discussion

4.1. Time series of averaged variances observed during FF2

Observed streamwise velocities u at three measurement heights in Figure 1a showed similar magnitudes to those observed before the fire front passage under a strong ambient wind of 9 m s^{-1} observed prior to the ignition (14:30-15:00 CST). Measured 1 Hz peak vertical velocities of 6 m s^{-1} at 6 m AGL and 9 m s^{-1} at 20 m AGL accompanied with a maximum plume temperature of 200°C observed at 6 m AGL compare well with the observations made at the same site under lighter ambient winds (Clements *et al*. 2007). However, a period of downdraft that was observed in Clements *et al*. did not occur during the FF2 due to the strong horizontal winds that are unfavourable for fire-induced circulations (Jenkins *et al*. 2001).

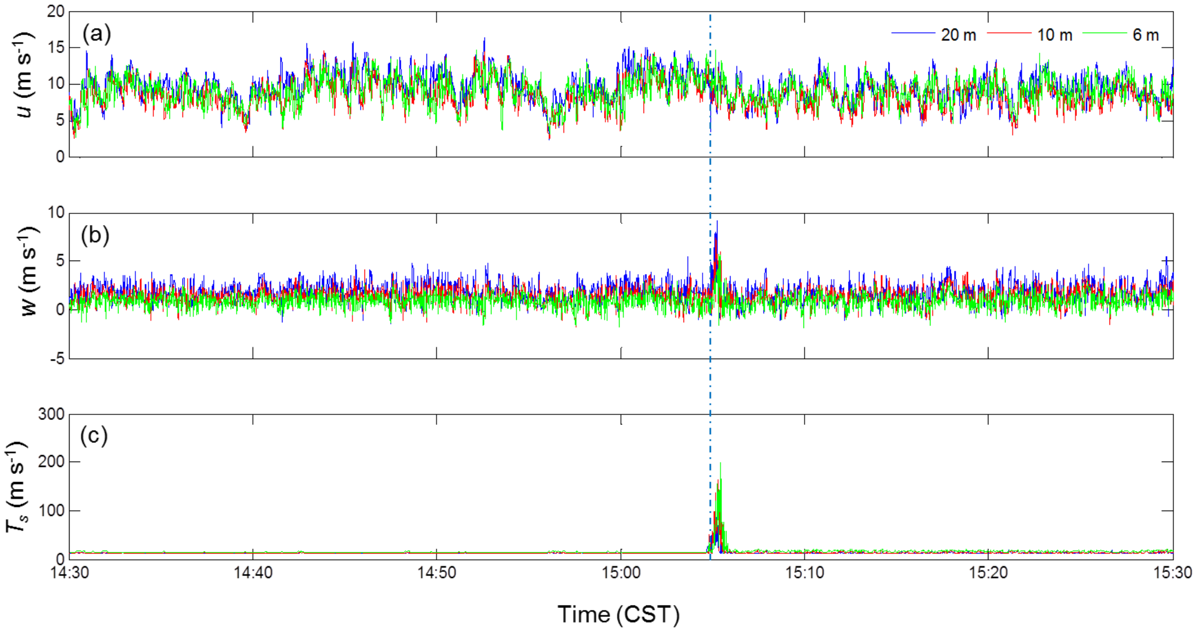

Figure 1. (a) streamwise velocity u, (b) vertical velocity w, and (c) sonic temperature T_s observed at the tower during FF2 experiment. Ignition was made at 15:04:08 CST, and fire front reached the tower around 15:05 CST as indicated by the sonic temperature spikes. Blue dashed line indicates the timing of the fire front arrival at the tower.

Figure 2 shows the *u* wavelet power averaged over three different scales/frequency bands, which give a measure of the scale-averaged variance in a certain band. Increased wavelet power over 2-4 s at 20 m, 10 m, and 6 m AGL at the time of the fire front passage suggests fire generated small-scale turbulence (2-4 s band) within the plume, where the strong updrafts were present. For larger scales than the 2-4 s band, the wavelet power remained below the ambient level over the fire, which suggest no major influence of the fire on the turbulence field for the scales (frequency) larger than 8 s (below 0.1 Hz). The strong mean winds were responsible for the large turbulent energy generation over the 8-16 s and 32-64 s scales on the background turbulence. The results indicate that fire-induced turbulence at larger scales may be supressed in the mean wind direction when the ambient winds are stronger than the fire's convection, and only smaller eddies, perhaps related to the entraining motions of the smoke plume, were enhanced by the fire.

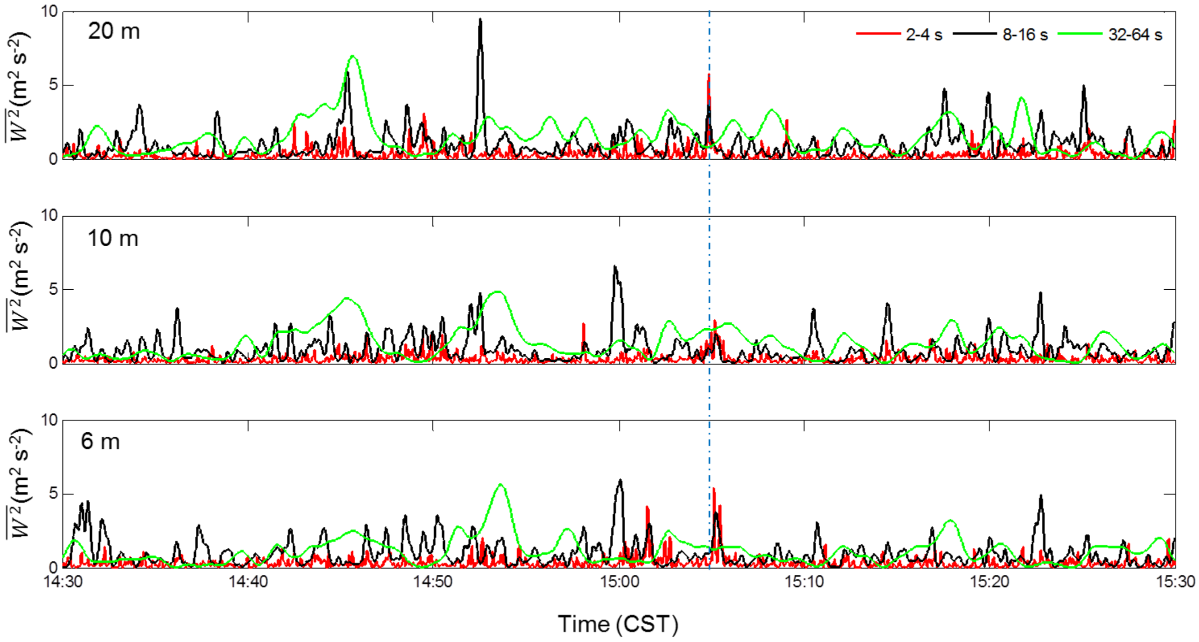

Figure 2. Scale-averaged wavelet power W^2 over the 2-4 s (red line), 8-16 s (black), and 32-64 s (green) bands for the u velocities measured at the main tower during the FF2. Blue dashed line indicates the timing of the fire front arrival at the tower.

The vertical velocity wavelet power shown in Figure 3 is well characterized by the large increases in 2-4 s scale variances at all three measurement heights. The magnitudes of their power were much larger than the variances at larger scales. The fire’s strong buoyancy generates turbulence in the vertical direction that is much smaller in scale than the atmospheric turbulence generated within the boundary layer.

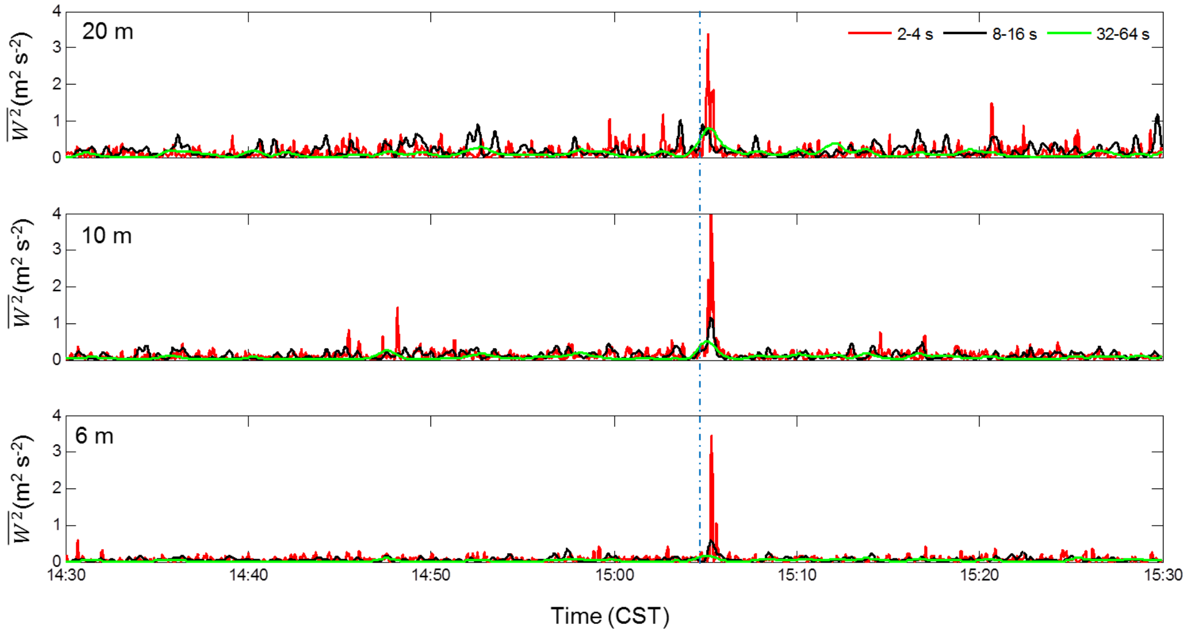

Figure 3. Scale-averaged wavelet power W^2 over the 2-4 s (red line), 8-16 s (black), and 32-64 s (green) bands for the w velocities measured at the main tower during the FF2. Blue dashed line indicates the timing of the fire front arrival at the tower.

4.2. Time series of averaged variances observed during NC

The steamwise velocity *u* at the canopy top (20 m AGL) shows larger fluctuations than those within the canopy (10 m and 3 m AGL) before and after the fire front passage, as indicated by high sonic temperatures near 100°C (Figure 4), due to the momentum absorption by the canopy layer. A head fire at 16:16 EST resulted in increased *u* velocities within the canopy and increased vertical motions at all three heights.

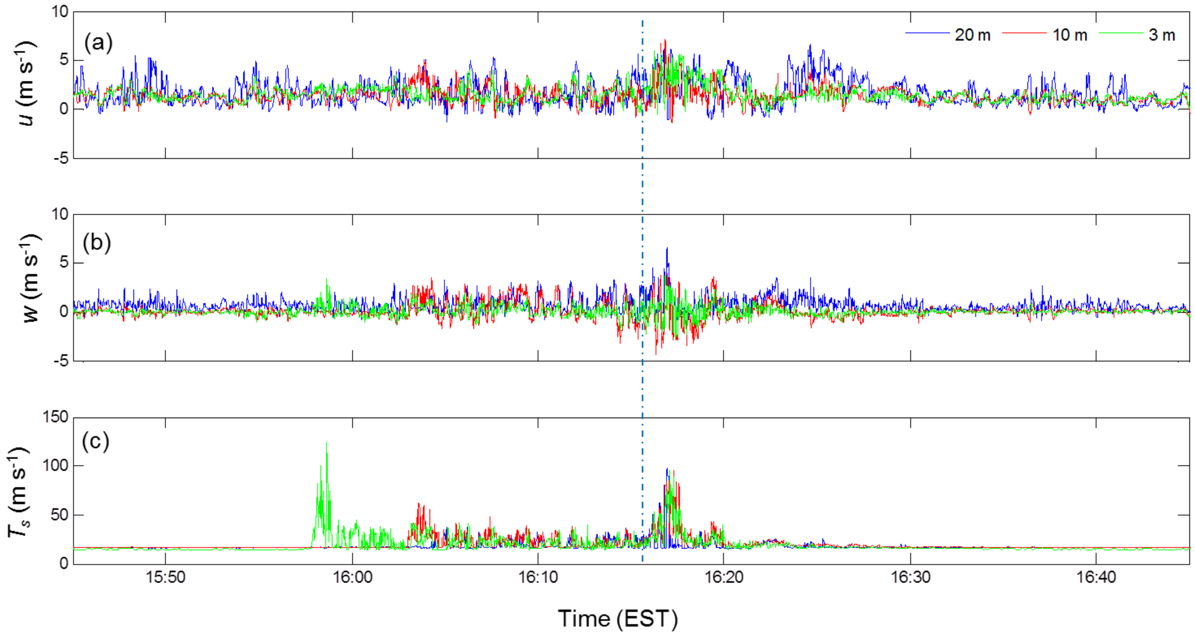

Figure 4. (a) streamwise velocity u, (b) vertical velocity w, and (c) sonic temperature T_s observed during NC experiment. Ignition was made at 11:04:08 EST. Blue dashed line indicates the timing of the fire front arrival at the tower.

The head fire at 16:16 EST was associated with increased *u* variances over the 2-4 s and 8-16 s bands both within and at the top of the canopy as compared to those observed prior to the head fire. It indicates that the turbulence structure within the plume was similar with height up to 20 m AGL. A coherent structure in the 32-64 s band variance may suggest turbulent mixing during the fire although the magnitudes of the variances observed within the canopy were still smaller than the ambient variance above the canopy. The increased wavelet variances within the canopy due to the fire were still smaller than the turbulence observed above the canopy, which indicates relatively weak turbulence generation from the low-intensity fire in the *u* direction.

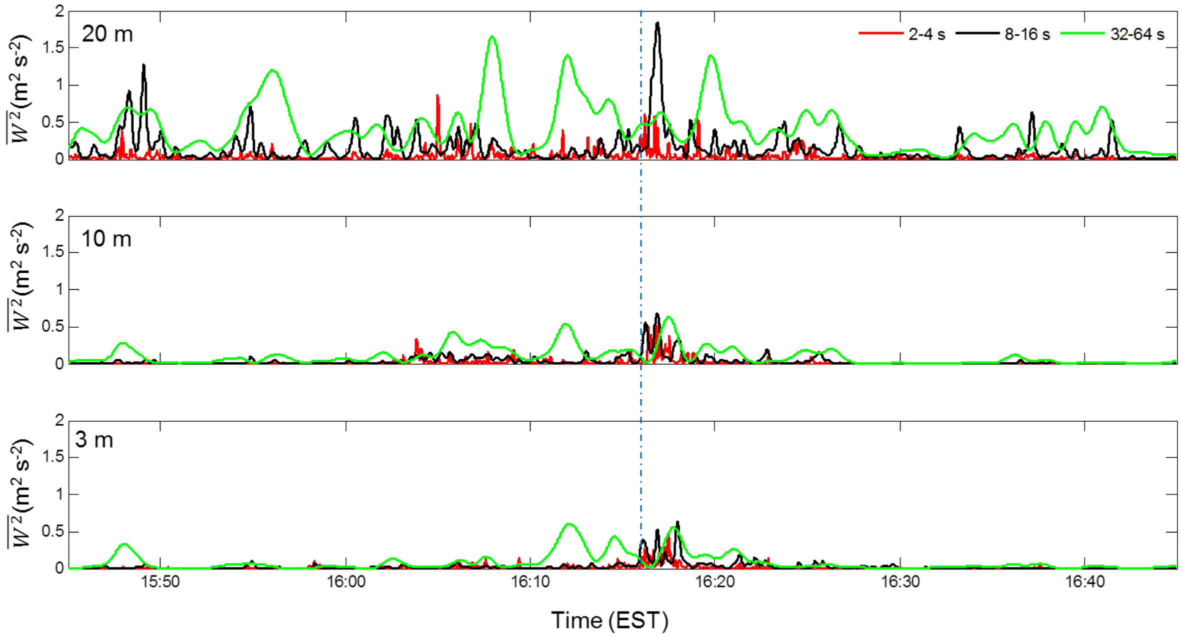

Figure 5. Scale-averaged wavelet power W^2 over the 2-4 s (red line), 8-16 s (black), and 32-64 s (green) bands for the u velocities measured at the main tower during the NC. Blue dashed line indicates the timing of the fire front arrival at the tower.

The vertical velocity variance at the canopy top was dominated by the 8-16 s band with a decreasing trend towards the ground. The *w* wavelet power over the 8-16 s band also shows a large spike similar to the *u* velocity component.

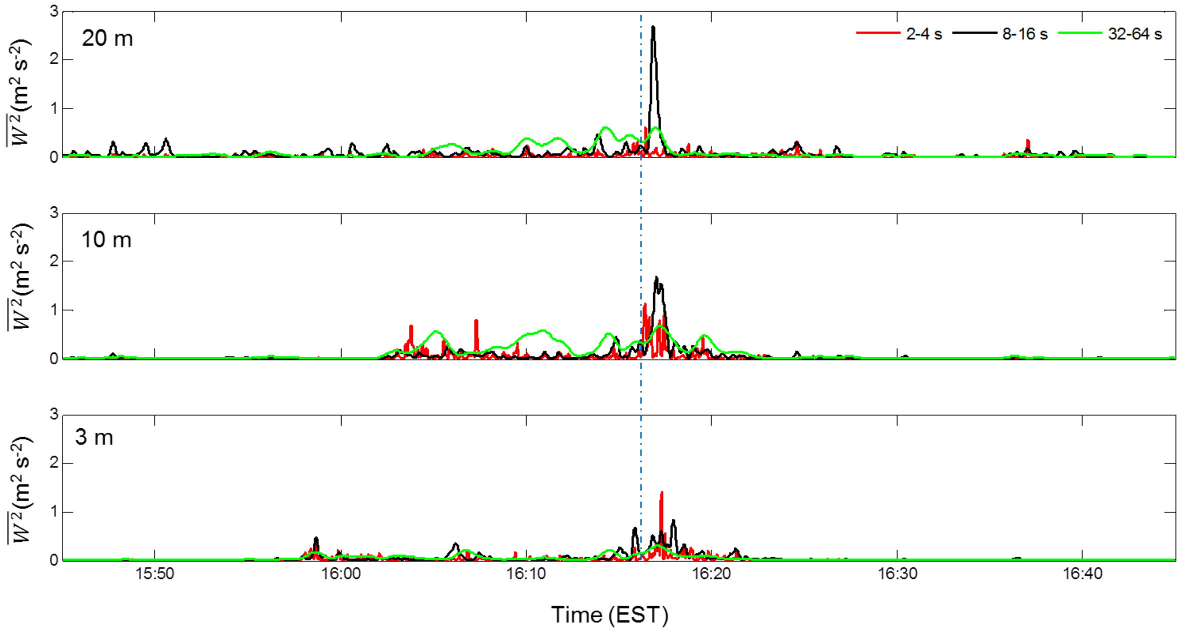

Figure 6. Scale-averaged wavelet power W^2 over the 2-4 s (red line), 8-16 s (black), and 32-64 s (green) bands for the w velocities measured at the main tower during the NC. Blue dashed line indicates the timing of the fire front arrival at the tower.

4.3. Comparisons between the two fires

The turbulence generated by the grass fire showed an increase limited primarily to the smaller (2-4 s) scale turbulence, whereas the sub-canopy fire contained slightly larger scale (8-16 s) turbulence structures. This may be associated intermittent convective smoke plume pulses of the low intensity sub-canopy fire. The magnitudes of the 2-4 s variances induced by the grass fire were 3 to 5 times larger in magnitude than those generated by the low intensity sub-canopy fire. The turbulence structure before and after the fire front passage did not show changes in the velocity spectral behaviour for the two fires under the observed conditions.

5. Conclusions

Turbulence structures in two experimental fires were examined using a continuous wavelet signal processing for a grass fire under strong ambient winds and a forest sub-canopy fire under light ambient winds. Only a small increase in u variance over the 2-4 s band was found during the fire front passage in the grass fire environment under the strong mean winds. The variance associated with low intensity sub-canopy fire was found to increase over 2-4 s and 8-16 s bands, due to the lower frequency smoke plume pulses. The turbulence structure before and after the fire front passage did not show changes in the velocity spectral behaviour for the two fires for the given conditions. Further analyses will include temperature variances and its relationship with the observed velocity variance signals.

6. Acknowledgements

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7. References

Clements, C. B., Zhong, S., Goodrick, S., Li, J., Bian, X., Potter, B. E., Heilman, W. E.,

Charney, J. J., Perna, R., Jang, M., Lee, D., Patel, M., Street, S., Aumann, G., 2007: Observing the Dynamics of Wildland Grass Fires: FireFlux- A Field Validation Experiment. Bull. Am. Meteorol. Soc. 88(9), 1369-1382.

Clements C.B., and Coauthors (2014) Overview of the 2013 FireFlux-II Grass Fire Field Experiment**,** *VII International Conference on Forest Fire Research*, D. X. Viegas (Ed.), 2014

Clark, T. L., Jenkins, M. A., Coen, J., Packham, D., 1996: A coupled atmosphere-fire model: Convective feedback on fire-line dynamics. J. Appl. Meteorol. 35, 875-901.

Jenkins, M.A., Clark, T., Coen, J., 2001: Coupling atmospheric and fire models, in: Johnson, E.A., Miyanishi, K. (Eds.), Forest fire: Behavior and ecological effects. Academic Press, pp. 257-302.

Seto, D., Clements, C. B., Heilman, W. E., 2013: Turbulence spectra measured during fire front passage. Agric. For. Meteorol. 169, 195-210.

Seto, D., Clements, C. B., Strand, T., Thistle, H., Mickler, R., 2014: Turbulence and plume thermodynamic structures during low-intensity subcanopy fires. Agric. For. Meteorol. *In review*.

Sun, R., Krueger, S.K., Jenkins, M.A., Zulauf, M.A., Charney, J.J., 2009. The importance of fire-atmosphere coupling and boundary-layer turbulence to wildfire spread. International Journal of Wildland Fire 18, 50-60.