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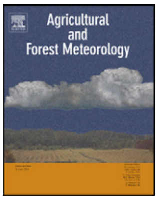

Turbulence spectra measured during fire front passage

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ABSTRACT

Four field experiments were conducted over various fuel and terrain to investigate turbulence generation during the passage of wildland fire fronts. Our results indicate an increase in horizontal mean winds and friction velocity, horizontal and vertical velocity variances as well as a decreased degree of anisotropy in TKE during fire front passage (FFP) due to fire-induced winds. Vertical velocity and temperature variances observed during FFP approached the local free convection prediction when represented as a function of stability parameter z/L under very unstable conditions. The results of our wavelet spectral analysis show increased energy in velocity and temperature spectra at high frequency during FFP for all four cases; we hypothesize this is caused by the shedding of small eddies generated from the fire front. Additionally, spectral energy of velocity components at low frequencies may be affected by cross-flow intensity, topography, presence of canopy layer, and degree of fire–atmosphere coupling. When the velocity spectra are normalized using the friction velocity u_* following Monin–Obukhov scaling, the velocity spectra observed during the FFP collapsed into a fairly narrow band in the inertial subrange, suggesting that as far as inertial range is concerned, the friction velocity u_* is a valid scaling parameter that can be used for wildfire application. When the temperature spectra are normalized by T_*, the temperature spectra observed during the FFP did not show any systematic behaviors predicted by the similarity scaling due to the extreme surface heating environment of fires.

1. Introduction

Recent advances in numerical modeling of fire–atmosphere processes make it possible to simulate both the small-scale fire–atmosphere interactions that occur at spatial scales on the order of tens of meters at the fire front and larger-scale atmospheric forcings affecting the entire fire area that occur at spatial scales on the order of kilometers (Jenkins et al., 2001). However, few, if any, studies have focused on the observed turbulence structure in the immediate environment of propagating fires to further understand the scales of the interaction and therefore, few principles exist from which to describe the behavior of strongly perturbed flow near the surface around the fire front. This is because conducting meteorological measurements near the fire front, even during prescribed fires, is challenging due to the risk of damaging the instrumentation. Consequently, detailed in situ turbulence measurements have been very limited.

In situ turbulence measurements made recently over flat terrain with grass fuels during the FireFlux experiment (Clements et al., 2007, 2008) showed increases in both horizontal and vertical velocity variances at the fire front, with the largest increase in the vertical velocity variance caused by convective motion from large heat flux. The turbulence spectral analysis of the vertical wind velocity, *w*, measured by Clements et al. (2008) revealed a general increase in the *w* spectral density at lower frequencies during the fire while the overall shape of the spectral density did not change in the high frequency range. The result suggests that large eddies induced by the fire may contribute to the overall turbulence generation. While the spectral analysis performed by Clements et al. (2008) provides useful information regarding spectral energy modified by a grass fire as reference spectra, more field observations of in situ turbulence data during fires are required for further comparisons. In addition, the spectral analysis of horizontal velocity components is necessary to fully understand the interaction of the fire with the atmosphere.

The ability to predict the rate of fire spread is one of the most important requirements for successful fire suppression, and operational fire spread rate predictions may be improved by accounting for the effect of turbulence and eddies in the ambient wind on fire spread (Sun et al., 2009). Albini (1982, 1983) attempted to combine an empirical representation for the power spectral density of horizontal wind near the ground with a theoretical model in order to predict the variability of fire spread rate and intensity of wind-aided free-burning line fires. His results suggest that free-burning line

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fires are responsive to wind speed variations in the frequency range below 0.1 Hz and fire intensity variations are likely to be nearly periodic at the very low frequency. Furthermore, he found the fire spread rate variability to be rather erratic, with standard deviations exceeding the mean value in many cases for timescales on the order of a minute. It should be noted, however, that power spectra of the fire spread rate and intensity in his study were derived from the wind speed at near mid-flame height in the absence of a fire on the site and therefore, the fire–atmosphere coupling or interaction was not included. Anderson et al. (1982) showed that slight changes in the wind speed observed both upwind from the ignition point and across the path of the fire produced substantial variations in the rate of spread of a head fire. The impact of fire-induced turbulence on the rate of spread variation could not be ruled out for the variations. Wind effects on the geometric and thermal properties of the flame front have been investigated at the field scale by Morandini et al. (2006). Their results suggest that the flame shape, temperature, and heat flux were affected by the observed large-scale wind fluctuations and therefore, they highlighted that the large-scale turbulence plays a significant role on fire spread. While their results provided useful information on the influence of wind on fire, more experiments under a wide range of wind conditions are essential to be more conclusive about the interaction between fire and turbulence.

The characteristics of the atmospheric surface layer (ASL) turbulence spectra have been studied extensively to explore whether data from different sites and heights with different stability conditions display a universal behavior in terms of Monin–Obukhov similarity theory (MOST; see Foken, 2006 for review) (Cava et al., 2001). Spectral analysis of the atmospheric turbulence, by decomposing a series of measurements into frequency components, allows for the general description of turbulence structure in terms of a few scaling parameters as power spectral density reveals how much of the variance is associated with a particular frequency. Within the framework of MOST, Kaimal et al. (1972) demonstrated that all spectra reduce to a family of curves so that they converge into a single set of universal curves in the inertial subrange with a $-5/3$ slope signature but diverge at lower frequencies according to the stability parameter z/L, where z is the measurement height and L the Obukhov length. While the systematic behavior of the velocity and temperature spectra found by Kaimal et al. (1972) supports MOST in terms of the behavior of inertial subrange and thus referred to as an ‘ideal’ reference for flat terrain, a number of recent studies have identified features that deviate from those predicted by MOST. For example, large scale turbulence is known to contribute the failure of MOST for observed turbulence structure (Katul and Chu, 1998; McNaughton and Laubach, 2000; Zhang et al., 2010). Intermittency may also lead to departure from the theoretical scaling (Kuznetsov et al., 1992; Katul et al., 1994).

The spectral characteristics of turbulence were investigated further to test the validity of the similarity theory under non-ideal conditions. In complex terrain, turbulence characteristics depend strongly upon changes in upwind surface roughness and therefore, it is difficult to draw firm conclusions about turbulence behavior modified by topography. Andreas (1987) showed that increased horizontal spectral energy at lower frequency is due to an effect of topography, and similar modification was also observed in the results by Al-Jiboori et al. (2001). Vertical velocity spectra were observed to be less affected by the effect of topography and thus display very similar spectral properties as those over homogeneous terrain (e.g. Panofsky et al., 1982; Al-Jiboori et al., 2001; Cava et al., 2001). It should be noted that studies of turbulence spectra in complex terrain were focused primarily on hills and changing surface properties rather than in mountain valleys.

Characteristics of turbulence spectra within different plant canopies have been studied extensively, and canopy spectra were summarized in Finnigan (2000). Liu et al. (2001) demonstrated that the maximum turbulent energy of the velocity and temperature inside the forest canopy shift toward higher frequencies as compared with previously observed spectra over flat terrain, emphasizing more contributions from smaller eddies. Their results also indicate that the normalized velocity and temperature spectra obey the $-5/3$ slope in the inertial subrange reasonably well, while Kaimal and Finnigan (1994) suggest a slightly steeper roll-off rate in the inertial subrange for the velocity spectra within the canopy.

The results of the spectral analysis for atmospheric motions have been used for parameterizing eddy diffusivities for air pollution applications (Yadav et al., 1996). For example, the eddy diffusivity coefficients can be specified by using the spectral maximum frequency. The turbulent dissipation rate, estimated from the inertial subrange of the spectra, could also be used for plume rise calculations (Yadav et al., 1996). Additionally, CALPUFF (Scire et al., 2000), a default dispersion model used in BlueSky smoke modeling framework (Larkin et al., 2009) for addressing local and regional smoke impacts caused by wildland fire, includes an option to estimate the dispersion coefficients σ_v and σ_z based on similarity theory. The validity of the similarity theory, however, must be questioned when used for wildland fire applications because the perturbed boundary layer over an extremely heated surface as fire propagates is not well understood in the micrometeorological sense. One of the reasons is the lack of appropriate experimental datasets that could be used to develop a conceptual framework for describing flow and turbulence in the wildfire environment.

Our overall objectives in this research are: (1) to investigate the properties of turbulence spectra over a surface during fire front passage (FFP) as compared to those before and after FFP, which allows us to directly measure the spectral energy generated by fire-induced turbulence; and (2) to revisit the validity of the surface layer similarity theory but with effects of fire dynamics coexisting with boundary layer turbulence. Since there is no other suitable conceptual framework related to the description of turbulence spectra from the surface layer with the presence of fire, this study represents an initial attempt to evaluate the applicability of similarity law in this type of environment.

2. Experiments and data description

Four field experiments were conducted between the years 2008 and 2010, each with its unique site and fire characteristics (Fig. 1 and Table 1). Time-series data from these four experiments are used in the subsequent analyses.

2.1. Experiment 1: grass fire in valley

This observational campaign was conducted during a vegetation management fire (prescribed burn) conducted by Cal Fire (California Department of Forestry and Fire Protection) on 7 October 2008 at Joseph D. Grant County Park (37°19′N, 121°42′W). The park is located in the Diablo Range approximately 6.5 km east of San José, California and 60 km east of the Pacific Ocean. The experimental site is located in a northwest-southeast oriented valley, with the valley bottom elevation of 440 m above Mean Sea Level (MSL) surrounded by ridges that rise 660 m on the west and 830 m on the east. A detailed description of the site is discussed in Seto and Clements (2011). The burn unit was 0.14 km^2 (35 acres) in size, dominated by grass fuels including Italian Rye (*Lolium multiflotun*), Oat Grass (*Avena barbata*), Soft Brome (*Bromus hordeaceus*), and Purple Needle Grass (*Nassella pulchra*). The soils were dry and fuels were fully cured. The estimated fuel loading was 0.12 kg m^{-2} (0.5 tons acre^{-1}). Burn operations initially started as backing fire (a fire set along the inner edge of a fireline to consume the fuel in