Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: William P. Antolin *et al* 2024 *J. Phys.: Conf. Ser.* **2885** 012076

Journal of Physics: Conference Series **2885** (2024) 012076 doi:10.1088/1742-6596/2885/1/012076

Wavelet analysis to reveal fluctuations in near-surface temperature and wind speed during the FireFlux I experimental fire

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Abstract. Field-scale wildland fire experiments are needed to validate coupled atmosphere/fire models and to assess their ability to represent wildland fire dynamics, including surface fire spread and perturbed local meteorology in the immediate vicinity of the spreading fire. These experiments provide access to the in situ turbulence observations needed to understand the local turbulent structures, which are impacted by the strong heat fluxes released by the fire and by the presence of forest canopies. In this paper, we present a wavelet analysis approach to extract turbulence information, based on frequency localization, from observed time series of temperature and wind speed during the FireFlux I experimental fire. Wavelets are used to robustly decompose the time series of interest into mean and fluctuation components by separating scales in the frequency space, where it is possible to identify the scales that contribute most to the energy spectrum. Fluctuations in temperature and wind speed are then used as input to a quadrant analysis to characterize the possible interactions between variables as the fire front passes, and to identify the most dominant events such as sweeps, puffing and local cooling. Wavelets therefore have great potential for observation-model comparison, i.e. for assessing the ability of coupled atmosphere-fire models to represent realistic turbulence patterns associated with atmosphere-canopy-fire interactions.

1. Introduction

Wildland fire behavior is strongly influenced by complex atmosphere-fire interactions. The release of heat and moisture from flaming combustion significantly perturbs near-surface wind flow and generates turbulence patterns, which become even more complex in a forested environment [2, 7, 8]. In particular, atmosphere-fire interactions influence the planning of low-intensity prescribed burns, which are necessary for fuel management but are likely to degrade air quality at wildland-urban interfaces [15].

Coupled atmosphere-fire models (e.g. [4]) aim to predict atmosphere-fire interactions at landscape-to-meteorological scales by representing the fire front propagation at the land surface and its coupling with the atmospheric dynamics (in particular, the fire-induced wind) using the large-eddy simulation paradigm. These coupled models provide access to spatially and temporally-resolved turbulent quantities, such as temperature and wind speed. Access to high-frequency turbulence measurements [6, 14, 15] is therefore of paramount importance for assessing the ability of coupled models to properly capture fire-induced momentum and heat fluxes, potentially impacted by forest canopies often present in the immediate fire environment.

In the absence of a fire, intermittent turbulent structures in forested environments are known to be characterized by strong sweeps (downbursts of turbulence into the canopy) and weak ejections (bursts of turbulence out of the top of the canopy), which contribute to the redistribution of heat and momentum in the lower atmospheric boundary layer [2]. Their length scales are of the order of canopy height and could therefore influence fire spread. During a fire, while intermittent flame sweeps and bursts have been documented and correlated to instabilities related to buoyancy and convection [9, 11], little is known about the underlying coherent structures responsible for this behavior. In particular, the question of how upstream atmospheric turbulence influences instability occurrence remains open. In this context, the role of the forest canopy requires further study, as the combined influence of fire and canopy induces complex turbulence patterns that need to be decomposed to better understand and predict the role of each factor in the heat and momentum fluxes released in the atmosphere [10, 13].

Quadrant analysis is an interesting approach to investigate these heat and momentum flux events during a fire [10, 11]. However, this requires distinguishing fluctuations from the mean flow between the ambient atmosphere and the fire-induced atmospheric conditions. In the literature, the inference of fire-induced coherent structures often involves Reynolds' decomposition, which is very sensitive to the choice of the averaging window [6]. In particular, mean values are often obtained using information prior to the fire [17], which may not be representative of the mean values during the fire due to the fire-induced wind effects. It is therefore necessary to define a more physical approach for estimating the fire-induced fluctuations, which is able to consider the full range of turbulence scales. Wavelet analysis as introduced by Collineau and Brunet [3] is a promising approach for scale separation as it can handle highly unsteady signals typical of wildland fires. However, in the wildland fire literature, wavelets have been mainly used for time localization. For example, Desai *et al.* (2024) [7] used wavelets to relate canopy ramp motions to fire behavior by carefully examining canopy ramp-cliff structures. Although wavelet analysis is used to infer event duration, the proposed approach still relies on a moving average window to estimate mean quantities, following the work of Heilman *et al.* [10]. In the present study, the application of wavelets is driven by a different objective, i.e. frequency localization [3, 12]. The objective here is to use wavelet analysis to decompose the flow time series into its mean and fluctuation components by separating scales in the frequency space according to their energy contribution. Conversely, a moving average window filters every frequency within the signal simultaneously, and assumes that all scales have the same contribution to the signal.

The aim of this paper is to show how wavelets [3] can be used to define, in an informed way, a filtering time scale to extract fluctuations from the time series during the fire front passage of the FireFlux I experiment [10], which occurs in the vicinity of forest canopies. These fluctuations provide inputs to the quadrant analysis, which is valuable to investigate the joint influence of fire and canopy on micrometeorology. This wavelet analysis is promising for the comparison of observed and simulated fluctuations obtained from a coupled atmosphere-fire model, in order to advance the coupled model validation process and data interpretation.

2. The FireFlux I experimental grass fire

The FireFlux I experiment [5, 6] was conducted in February 2006 in Texas, USA. A 30-ha plot, shown in Fig. 1 and made of tall grass with an average height of 1.5 m and a fuel load of 1.08 $\mathrm{kg\,m^{-2}}$, was burned. The fire was ignited at 12h43:30 local time on the north side of the plot under ambient near-surface northeasterly winds of approximately 3 $\mathrm{m\,s^{-1}}$. The fire lasted 15 min and spread as a head fire from north to south, at an average rate of spread of 1.6 $\mathrm{m\,s^{-1}}$ between the two instrumented towers (blue dots in Fig. 1). Measurements of temperature (T) and wind speed (e.g. streamwise component V) were recorded at the two towers (from 2.1 to 43 m AGL at the main tower). Here the 1-Hz main tower observations provided by San José State University are used for the analysis and correspond to a 1-h window (including the burn).

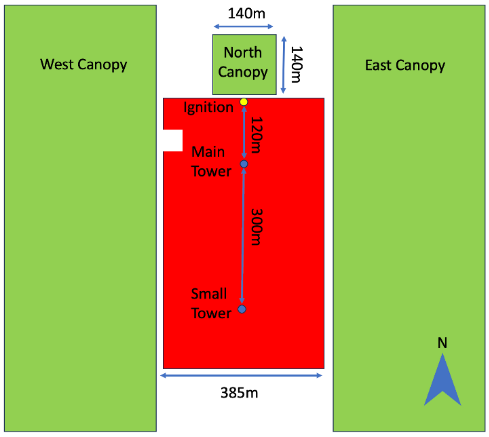

Figure 1: Schematic of the FireFlux I experiment. The red box represents the 30-ha burn plot; the yellow circle represents the ignition point; the blue circles represent the two instrumented towers; and the green boxes represent the canopy blocks.

3. The wavelet analysis approach

Wavelet analysis [3] provides a time-frequency representation of a given signal. Unlike the global Fourier transform, which localizes the signal strictly in the frequency domain and loses all temporal information, wavelet analysis operates on a scale-by-scale basis. This makes it suitable for revealing deviations from the mean signal and thus for studying intermittent processes.

Mathematically, the wavelet transform convolves the signal h with a selected wavelet function g, to examine the similarity between h and the wavelet family $\{g_{a,b,p}(t)\}$ corresponding to all possible translations and dilations of the base wavelet g to match a given scale a at each time lag b. This yields wavelet coefficients $T_p(a,b)$, which capture the signal characteristics:

$$T_p(a,b) = \int_{-\infty}^{+\infty} h(t)\, g_{a,b,p}(t)\, dt = \frac{1}{a^p} \int_{-\infty}^{+\infty} h(t)\, g\left(\frac{t-b}{a}\right) dt. \tag{1}$$

The wavelet variance $W_p(a)$ can be obtained by integrating the wavelet coefficients over the translation parameter b, giving access to the energy distribution across the scales a:

$$W_p(a) = \int_{-\infty}^{+\infty} \mid T_p(a,b) \mid^2 db. \tag{2}$$

This quantity is useful to detect sudden changes in the signal of interest h; the main peaks identify the most significant energy contributions and can be linked to specific scales a. Provided we can obtain a clear separation of scales in the energy distribution, we can filter the original signal h by performing an inverse wavelet transform on a sub-interval of the scale parameter a. For example, if a threshold scale a_0 is identified, we can decompose h into the sum of a low-frequency component ($a > a_0$) and a high-frequency component ($a < a_0$):

$$h(t) = \widetilde{h}_L(t) + \widetilde{h}_H(t). \tag{3}$$

In practice, we use the ssqueezepy library for wavelet analysis, with the usual exponent $p = 1$ and the Morlet complex function for g [16].

4. Application to the FireFlux I time series data

The continuous wavelet transform is applied to the time series of 2-m temperature (T) and streamwise wind speed component (V) at the main tower. Figure 2 shows the resulting scalograms, or wavelet coefficients (Eq. 1). Each scalogram is a 2-D map including both temporal and spectral information, where low frequencies correspond to large atmospheric structures that last a long time period (they are "stretched" in the time x-direction), and high frequencies correspond to small eddies linked to dissipation that last for a short time (they are "stretched" in the frequency y-direction). The transition from low-to-high frequencies occurs between the orange and the red horizontal lines, where a change in the structure size is visible, which would imply that the desired separation scale a_0 (see explanations in Sect. 3) is in this frequency range. We observe a strong amplitude in the scalograms between 2,500 and 3,000 s for the two quantities of interest. This time interval corresponds to the burning, and the highest intensity is obtained for the small scales (i.e. frequencies above the orange horizontal line). For temperature, the fire signature in the scalogram affects all scales. For the streamwise velocity component (V), most scales are active, but there is a fire-induced wind intensification in the small scales and the presence of a large structure that remains after the fire has passed.

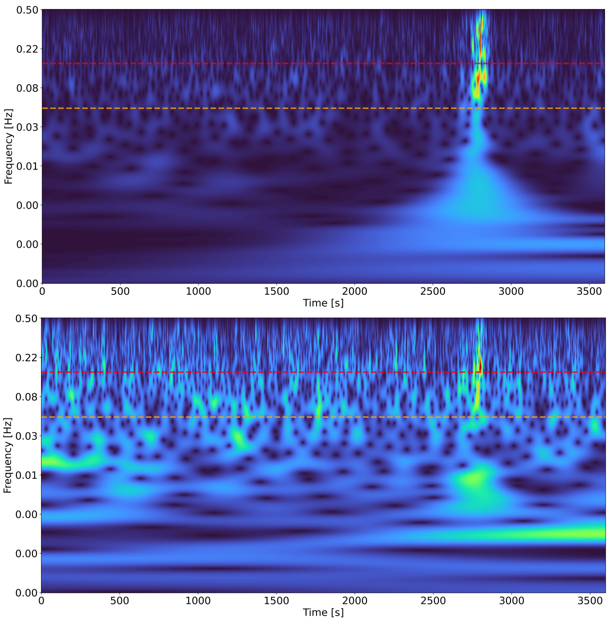

Figure 2: Wavelet coefficients for the T (top) and V (bottom) time series at 2 m height at the main tower. The x-axis corresponds to the 1-h time window; and the y-axis corresponds to frequency (or scales). High intensities correspond to warm colors (yellow-red) and low intensities to cool colors (blue-black). Colored horizontal lines correspond to specific values of the scale parameter a.

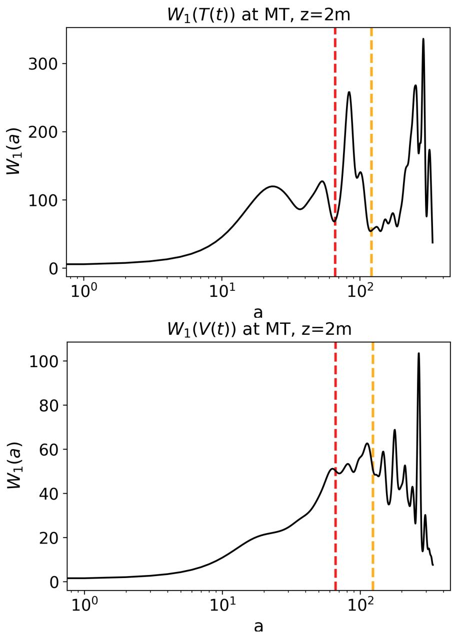

Figure 3: Variance diagrams of the T (top) and V (bottom) time series at 2-m height at the main tower across the scales a. The scale separation is done visually based on the temperature variance by locating the variance curve dips.

The variance plots in Fig. 3 are obtained by integrating the wavelet coefficients in Fig. 2 over the translation parameter b. Even if the temporal dimension is lost, this variance information is of interest as it gives the energetic distribution of the scales contained in the signal. Peaks in the variance indicate a strong energetic contribution attributed to a particular scale a. The variance

Journal of Physics: Conference Series **2885** (2024) 012076 doi:10.1088/1742-6596/2885/1/012076

dips are thus considered as potential scale separation threshold. The dilation parameter a_0 corresponding to the orange line in Fig. 3 is found to provide an appropriate filtering separating the mean and the fluctuations of the time series for T and V. Indeed, the low-frequency signal is too noisy when using the red line in Fig. 3 to define the scale threshold a_0 and cannot be interpreted as the signal mean in Fig. 4. Conversely, the low-frequency signal associated with the orange line sufficiently smoothes the signal while retaining the most important information.

Based on the choice of this dilatation parameter a_0, fluctuations can be derived from the discrepancies between the raw and mean signals. The temperature fluctuations T' are then plotted against the streamwise velocity fluctuations V' in Fig. 4 to carry out quadrant analysis during fire front passage. The principle is to decompose the joint streamwise velocity-temperature probability distribution into four possible quadrants or events: injection or ejection of air for positive and negative velocity fluctuations, and hot or cold events for positive and negative temperature fluctuations. In terms of occurrence, the most dominant modes are found to be hot air ejections (mode Q1 corresponding to $T' > 0$ and $W' > 0$), and cold air injections (mode Q3 corresponding to $T' < 0$ and $W' < 0$), with Q3 being slightly more dominant than Q1. Interestingly, the most dominant modes in terms of intensity come from the injection of both hot and cold air (modes Q2 and Q3), suggesting bursts intermittently feeding the fire. Such events could be associated with an intensification of combustion, a local increase in the rate of spread, and strong updrafts possibly associated with puffing [9, 11].

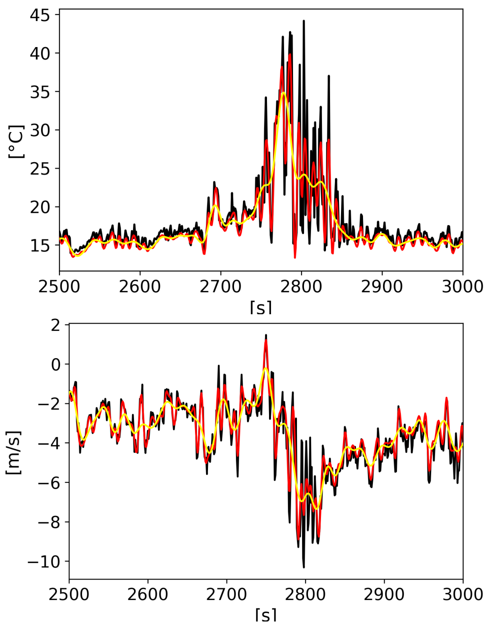

Figure 4: T and V time series at 2-m height at the main tower. Black (color) curves are raw data (mean signals related to scale separation in Fig. 3).

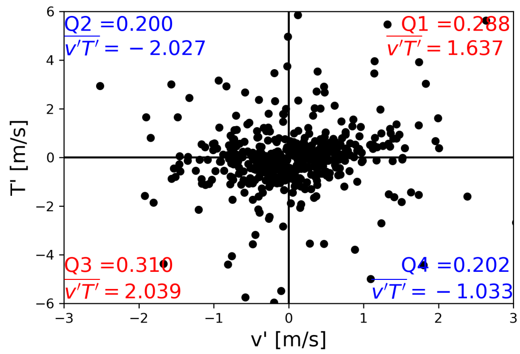

Figure 5: Quadrant analysis for T and V fluctuations at 2-m height at the main tower. The % of time spent in each quadrant over the time window is denoted by Qi, and the spread in each quadrant is also indicated.

5. Conclusions and perspectives

In this work, in the context of the FireFlux I experiment, wavelet analysis is found to be a robust approach for identifying the scales involved in the near-surface temperature and streamwise wind speed time series, and for extracting fluctuations during the passage of the fire front. From a methodological viewpoint, the approach could be further improved by finding a more objective criterion to choose the scale separation threshold. From an applicative viewpoint, analyzing the joint velocity-temperature distribution is valuable to understand fire dynamics. Similar analysis with the wind velocity components is helpful to characterize the sweep-ejection dynamics and thereby the combined influence of fire and canopy. Wavelet analysis is also currently applied to a coupled atmosphere-fire model [1], to evaluate its ability to capture turbulence patterns and represent forest canopy effects. In the longer term, wavelet information could be used to improve heat flux parameterization in coupled models.

Acknowledgments

The authors acknowledge C. Clements and A. Costes for providing access to the FireFlux I dataset, and R. Paugam and Y. Brunet for discussion on experimental fires and wavelets.

References

[1] Antolin, W., Rochoux, M., and Le Moigne, P. (2024) The role of forest canopy-wind interactions on experimental fire behavior using coupled atmosphere-fire modeling. EGU General Assembly, EGU24-17604.
[2] Brunet, Y. (2020). Turbulent flow in plant canopies: Historical perspective and overview. Boundary-Layer Meteorology, 177: 315–364.
[3] Collineau, S., and Brunet, Y. (2013). Detection of turbulent coherent motions in a forest canopy. Part I: Wavelet analysis. Boundary-Layer Meteorology, 65: 357–379.
[4] Costes, A., Rochoux, M.C., Lac, C., and Masson, V. (2020). Subgrid-scale fire front reconstruction for ensemble coupled atmosphere-fire simulations of the FireFlux I experiment. Fire Safety Journal, 126: 103475.
[5] Clements, C.B., Zhong, S., Goodrick, S., Li, J., Potter, B.E., Bian, X., Heilman, W.E., Charney, J.J., Perna, R., Jang, M., Lee, D., Patel, M., Street, S., and Aumann, G. (2007). Observing the dynamics of wildland grass fires. Bulletin of the American Meteorological Society, 88: 1369—1382.
[6] Clements, C.B., Zhong, S., Bian, X., Heilman, W.E., and Byun, D.W. (2008). First observations of turbulence generated by grass fires. Journal of Geophysical Research, 113: D22102.
[7] Desai, A., Guilloteau, C., Heilman, W.E., Charney, J.J., Skowronski, N.S., Clark, K.L., Gallagher, M.R., Foufoula-Georgiou, E., and Banerjee, T. (2024). Investigating fire-atmosphere interaction in a forest canopy using wavelets. Boundary-Layer Meteorology, 190: 21.
[8] Dupuy, J-L., Pimont, F., Linn, R.R., and Clements, C.B. (2014). FIRETEC evaluation against the FireFlux experiment: preliminary results. In: Viegas DX (ed) Advances in forest fire research. Coimbra University Press, Coimbra, pp 261–274.
[9] Finney, M., Cohen, J., Forthofer, J., McAllister, S., Gollner, M., Gorham, D., Saito, K., Akafuah, N., Adam, B., and English, J. (2015). Role of buoyant flame dynamics in wildfire spread. Proceedings of the National Academy of Sciences, 112(32): 9833–9838.
[10] Heilman, W.E., Banerjee, T., Clements, C.B., Clark, K.L., Zhong, S., and Bian, X. (2021). Observations of sweep–ejection dynamics for heat and momentum fluxes during wildland fires in forested and grassland environments. Journal of Applied Meteorology and Climatology, 60: 185-–199.
[11] Katurji, M., Noonan, B., Zhang, J., Valencia, A., Schumacher, B., Kerr, J., Strand, T., Pearce, G., and Zawar-Reza, P. (2022). Atmospheric turbulent structures and fire sweeps during shrub fires and implications for flaming zone behaviour. International Journal of Wildland Fire, 32(1): 43–55.
[12] Kumar, P., and Foufoula-Georgiou, E. (1997). Wavelet analysis for geophysical applications. Reviews of Geophysics, 35(4): 385–412.
[13] Mueller, E., Mell, W., and Siemoni, A. (2014). Large eddy simulation of forest canopy flow for wildland fire modeling. Canadian Journal of Wildfire Research, 44: 1534–1544.
[14] Mueller, E., Skowronski, N., Clark, K., Gallgher, M., Kremens, R., Thomas, J.C., El Houssami, M., Filkov, A., Hadden, R.M., Mell, W., and Siemoni, A. (2017). Utilization of remote sensing techniques for the quantification of fire behavior in two pine stands. Fire Safety Journal, 91: 845-854.
[15] Prichard, S., Larkin, N.S., Ottmar, R., French, N.H., Baker, K., Brown, T., Clements, C., Dickinson, M., Hudak, A., Kochanski, A., Linn, R., Liu, Y., Potter, B., Mell, W., Tanzer, D., Urbanski, S., and Watts, A. (2019). The Fire and Smoke Model Evaluation Experiment – A plan for integrated, large fire–atmosphere field campaigns. Atmosphere, 10(2).
[16] Schaller, C., Göckede, M., and Foken, T. (2017). Flux calculation of short turbulent events-comparison of three methods. Atmospheric Measurement Techniques, 10(3): 869–880.
[17] Seto D., Clements C.B., and Heilman W.E. (2013). Turbulence spectra measured during fire front passage. Agricultural and Forest Meteorology, 169: 195–210.