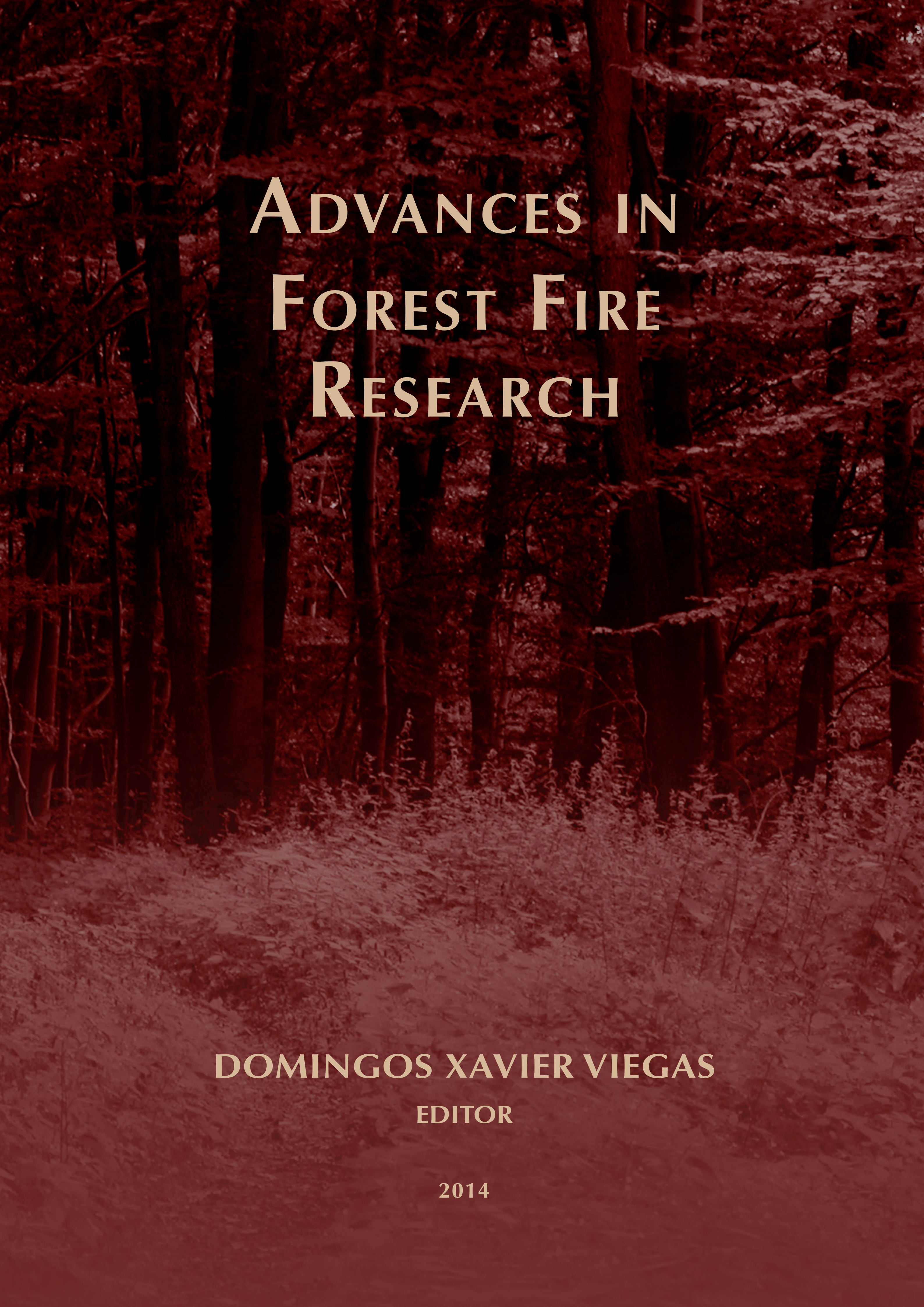

ADVANCES IN FOREST FIRE RESEARCH

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Experimental evidence of buoyancy controlled flame spread in wildland fires

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Abstract

Laboratory fires spreading through laser-cut cardboard fuel beds were instrumented and analyzed for physical processes associated with spread. Flames in the span-wise direction appeared as a regular series of peaks-and-troughs that scaled directly with flame length. Flame structure in the stream-wise direction fluctuated with the forward advection of coherent parcels that originated near the rear edge of the flame zone. Thermocouples arranged longitudinally in the fuel beds revealed the frequency of temperature fluctuations decreased with flame length but increased with wind speed. The behaviors are remarkably similar to those of boundary layers, suggesting a dominant role for buoyancy in determining wildland fire spread.

Keywords: *Flame Structure, Buoyancy, Instability, Flame Spread*

1. Introduction

Despite decades of research on wildland fires, a common understanding has not emerged as to how heat transfer processes are organized to produce fuel particle ignition and flame spread. This has left physical modelling of wildland fires without an experimental basis for the many assumptions, including radiation and convective heat transfer. Strong experimental evidence has now suggested a secondary role for radiation in flame spread in fine fuel beds because 1) the optical attenuation through the fuel bed diminishes irradiance to particles, and 2) cooling by forced or natural convection efficiently prevents fine fuels from reaching ignition. Thus, we focus here on recent laboratory and field experiments designed to determine how convective heating occurs. We found clear evidence that non-steady heating by flame contact produces fuel particle ignition.

2. Methods

Laboratory fire spread experiments were conducted in uniform fuel beds made of laser-cut cardboard. Cardboard and paper strips have been used previously (Emmons and Shen, 1971) and offer advantages of known homogenous properties such as density and customizable physical dimensions of discrete particles (length, surface area etc.). Fuel beds were burned in the wind tunnel at the Missoula Fire Sciences Laboratory. The wind profiles of the 3m cross-section have been described previously (Rothermel and Anderson 1966, Catchpole *et al*. 1998) and are laminar except along the bottom surface where an upstream trip-fence produces a turbulent boundary layer. Wind speeds were varied from 0.22 m s^{-1} to 2.3 m s^{-1} with relative humidity of approximately 25%.

Figure 1. Picture of laser-cut cardboard laboratory fuel bed. Note that the scale is graduated in inches.

Fuels for the laboratory burns were engineered from cardboard with a commercial CO_2 laser system to produce fuel elements that are connected at regular spacing along a common spine. The cards or "combs" could then be arranged in rows at various spacing to form a fuel bed with vertically standing particles (Figure 1). The cardboard used was brown "chip board" 1.27mm (0.05 inch) thick with approximately 60% recycled content. Fuel particles were created at different lengths and widths and arranged at different row spacing to achieve specific fuel bed properties. The laser cutter/engraver system was a Universal Laser Systems Inc. ILS12.150D model equipped with two 60W laser cartridges. The beams from both lasers were collimated for cutting. The table accommodates sheets of cardboard 0.61m X 1.22m (2 ft X 4 ft) so that multiple combs can be cut from the same sheet in one operation.

Fuel beds constructed of these cardboard combs were 1.22m to 2.45m in width and 3.05m to 6.1m in length (Figure 1). The combs were supported and arranged on a foundation of cement-board strips (Hardy Board) 0.635cm x 5.08cm (1/4 in. x 2 in) each separated by a steel spacer 0.158cm x 2.54cm (1/16 in x 1.0 in). The steel spacers rested on the floor to preserve a slot at the upper surface which pinched the spine of the fuel combs such that only the vertical tines were exposed (Figure 1). Tine lengths of 2.54cm (1in), 10.1cm (4in), 20.3cm (8in), and 35.6cm (14in) were used in the burns. The longitudinal spacing of the combs could be adjusted every 1.43cm (5/16in). To limit inflow to the combustion zone along the lateral edges during burning, the sides of the beds were lined with paper that was treated with the flame retardant Diammonium Phosphate ($(NH_4)_2HPO_4$). This technique was described by Byram *et al.* (1964), where fire retardant limits independent flaming combustion but allows the paper to burn in conjunction with the advancing fire front. The consumption of the paper sideliners at the trailing edge of the burning zone avoids channelling of air inflow to the rear of the fire which has been shown to affect fire spread on slopes (Smith 1992). Cutouts of the sideliner permitted filming of the ignition process within the fuelbed.

Field-scale fires were assessed to determine potential scaling relationships beyond those possible within the laboratory. At Fort Swift, Texas, grass 1 m deep was burned on separate plots with average winds of 1.7 m s^{-1} and 4.5 m s^{-1} and produced flames of approximately 3m tall. A rectangular wooden crib was also constructed of square ponderosa pine lath 0.025 m thick at 0.12x0.12 m square spacing with overall dimensions of (1.2m wide, 1m tall, and 17m long) and was burned to provide stationary flame source with approximately 6 m flames.

3. Results

The unprecedented uniformity of the fuel beds from engineered cardboard allowed us to observe flame structure and behaviour isolated from environmental heterogeneity. The first and most obvious characteristic of flame fronts in these flame sources is the peak and trough pattern of the flame edge (Figure 2). This geometry is similar to instabilities in boundary layer flow caused by Taylor-Görtler vortices, oriented in the flow direction, that arise when air inflow to the flame zone is lifted by buoyancy (Floryan 1991). From the literature (*e.g.* Sparrow and Husar 1969), studies of flow over heated plates and of boundary layer transition, pairing of counter-rotating Taylor-Görtler vortices form an alternating series of convergence zones in the transverse direction – with downward force creating the flame trough and up-ward convergence in flame peaks (Figure 2). The significance of these vortices is that they force flame down and forward into the fuel bed and advect secondary instabilities forward through the flame zone. Data from spreading wind tunnel fires, prescribed grassland burns, and stationary crib fires all reveal that the transverse wavelength of these vortices is about ½ the flame length (Figure 2D).

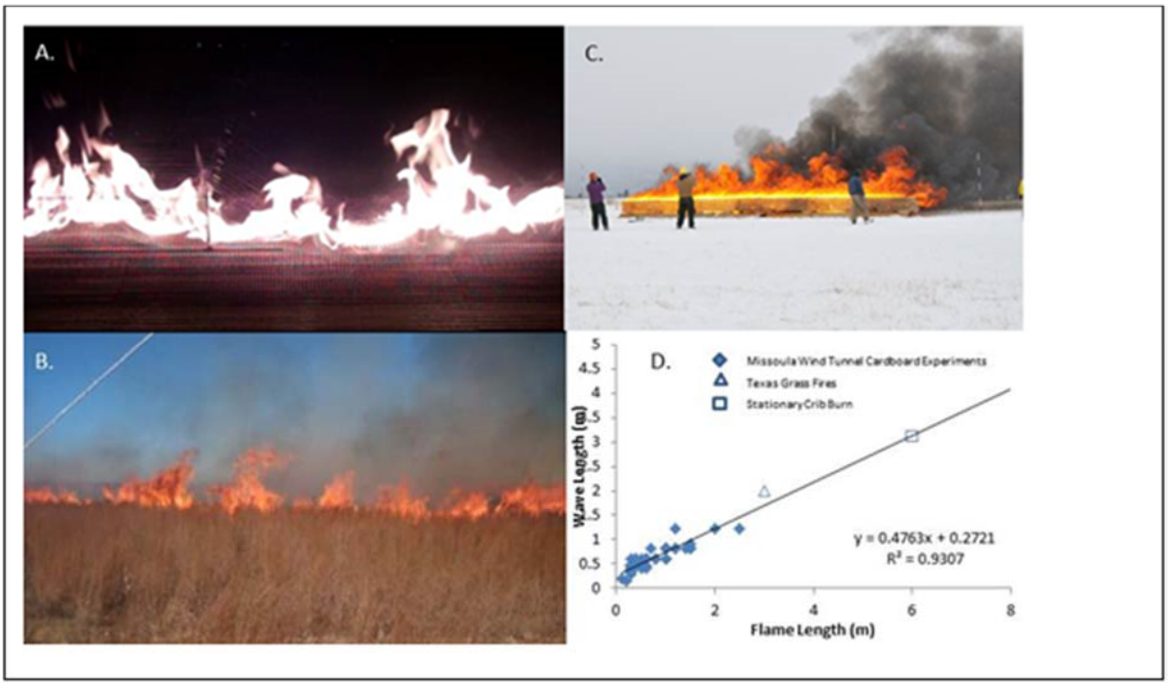

Figure 2. Flame structure in laboratory-scale cardboard fuel beds (2A) reveal the same sawtooth flame structure as grass fires (2B) and stationary crib fires (2C) because of Taylor- Görtler vortices. The transverse wavelength of these flame peaks appears to be about ½ the flame length from all of these fires (2D).

The second dynamic discovered in these experiments is a series of flame parcels (Figure 2a) which are first seen to originate near the back edge of the flame zone. These parcels remain coherent on video and move forward through the flame zone to burst forward and impinge fuel particles for some considerable distance ahead of the combustion interface. Thermocouple temperatures measured in the fuel beds (Figure 3b) fluctuate with predictable average frequencies that showed strong Strouhal-Froude scaling (Figure 3c) similar to the pulsing frequency from pool fires (Malalakasera 2006). This scaling, using the variables of wind speed and flame length, means the bursts frequency increases with wind speed and decreases with flame size. The origin of the bursts appears to be from instabilities arising at the upstream edge of the flame zone similar to Tollmien-Schlichting waves observed in boundary layer instabilities (Floryan 1991). These are visible first as transverse ridges and concave packets in the upper flame surface (Figure 3A). With downstream movement through the flame zone they are drawn into the circulations from Görtler vorticity and expelled forward past the leading flame edge into the fresh fuels ahead. This bursting frequency was recorded as temperature spikes on thermocouple arrays embedded in the fuel bed (Figure 3B) which demonstrate the coherency of the flame structures as they advect through the flame zone. Remarkably, data from all field sources suggests consistent Str-Fr scaling as laboratory-scale fires (stationary or spreading) (Figure 3C).

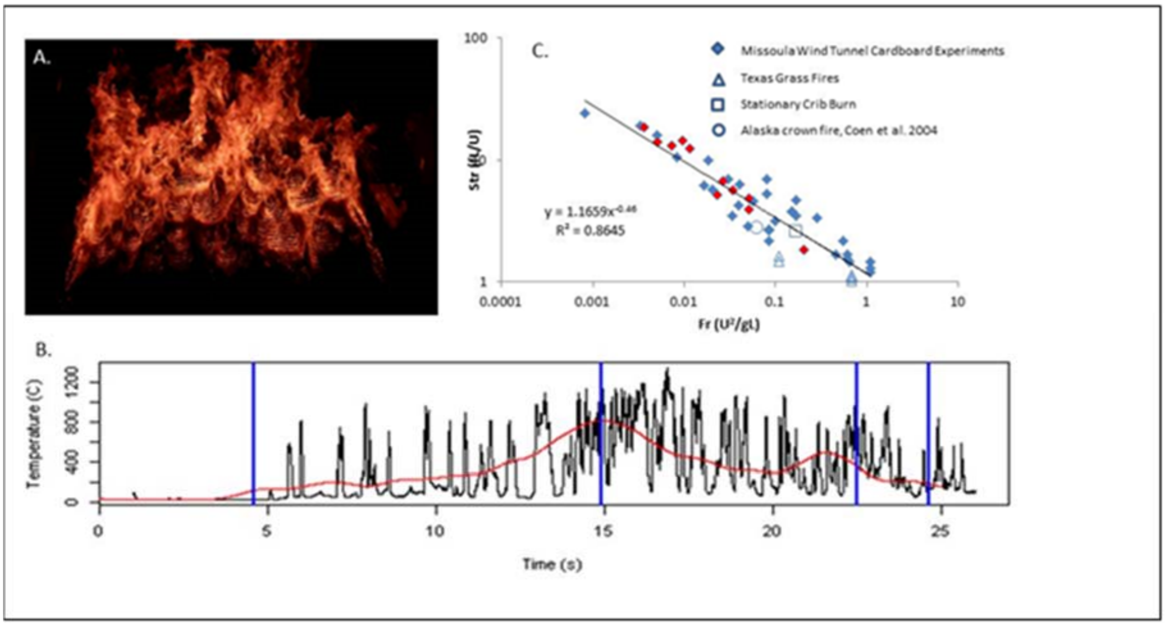

Figure 3. Instabilities in the flame zone are revealed in experimental fires burning in cardboard fuel beds as dish-shaped patterns originating near the rear edge of the flame zone (3A). These produce forward bursts of flame ahead of the combustion interface that result in a pulsing-type temperature signal on thermocouples (3B). Average burst frequencies (f) scale with a Strouhal-Froude correlation (Str-Fr, 3C) using windspeed (U) and flame length (L) of laboratory and field-scale fires (see Figure 2).

4. Discussion

This research reveals instabilities of the flame that are similar to buoyant dynamics of non-reacting flows (Floryan 1991). These instabilities appear responsible for creating flame intermittency at the leading edge of spreading fires and forcing flames downward into the fuel bed. Similar flame structure and intermittency was recently found using stationary gas flames, with and without forced flow[2]. The use of the Str-Fr scaling of non-steady flame behaviours in both studies suggests broad applicability across a wide range of wildland fire sizes and fuel[3]. The strong dependency of intermittent convective

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heating to thermal behaviour and ignition of individual fuel elements to radiation and convection is revealed in two other studies[4],[5].

Quasi-periodic flame behaviour in spreading fires has been noticed previously for trench fires for pine needle beds, but the role of such non-steady flame impingement in igniting fuel particles and flame spread has not been considered (Atkinson *et al.* 1995, Woodburn and Drysdale 1998, and Dupuy *et al.* 2011). The Strouhal-Froude scaling suggested by our data is consistent with buoyant dynamics of stationary fire phenomena (Malalasekera *et al.* 1996) but new to spreading fires. These findings suggest that the difficulty of identifying an integral length scale for convection related to ignition (Anderson *et al.* 2010) comes from assuming away the time-dependency of particle heating. It also suggests by virtue of the inverse dependency of average pulse frequency on flame dimensions that slower buoyant dynamics of larger flame zones compensate for the increases in energy release and convective heating distance to avoid runaway spread. If buoyant instabilities are responsible for the flame behaviours and particle ignition, then it strongly suggests that laboratory-scale fire spread processes should extend readily to field proportions because flame temperature in diffusion flames (and thus buoyancy) remains approximately the same regardless of fire size. At this time, our limited field-scale experiments and observations seem to be in agreement with this scaling. Much work is yet to be done to understand useful scaling relationships, but the ultimate goal is to someday incorporate these findings into practical tools for wildland fire managers.

5. Conclusions

These findings may have profound influence on understanding of the flame spread process in wildland fires because they suggest that buoyant dynamics govern the heat transfer processes. Thermocouple measurements on fuel particles show that ignition commences after a series of flame contacts that increase the particle temperature in discrete jumps. This is far from the normally assumed steady processes of particle heating. Even large particles in uniform fuel beds show these temperature jumps from flame contact and do not ignite by radiation because optical attenuation reduces irradiance dramatically.

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