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Atmospheric turbulence and wildland fires: a review

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ABSTRACT

The behaviour of wildland fires and the dispersion of smoke from those fires can be strongly influenced by atmospheric turbulent flow. The science to support that assertion has developed and evolved over the past 100+ years, with contributions from laboratory and field observations, as well as modelling experiments. This paper provides a synthesis of the key laboratory- and field-based observational studies focused on wildland fire and atmospheric turbulence connections that have been conducted from the early 1900s through 2021. Included in the synthesis are reports of anecdotal turbulence observations, direct measurements of ambient and fire-induced turbulent flow in laboratory and wildland environments, and remote sensing measurements of fire-induced turbulent plume dynamics. Although considerable progress has been made in advancing our understanding of the connections between atmospheric turbulence and wildland fire behaviour and smoke dispersion, gaps in that understanding still exist and are discussed to conclude the synthesis.

Keywords: atmospheric turbulence, fire behaviour, measurements, plumes, smoke dispersion, synthesis, vortices, wildland fires.

Introduction

Science-based investigations of the interactions between the atmosphere and wildland fires have a long history. Potter (2012*a*, 2012*b*) carried out an extensive review of research that has been conducted from the early 20th century to the early 21st century on atmospheric interactions with wildland fire behaviour. Many of the studies included in that review briefly touched on the topic of atmospheric turbulence (i.e. the gustiness of air flow) and its connection to properties or processes of the atmosphere that can directly or indirectly impact wildland fire behaviour and smoke dispersion.

Stull (1988) noted that turbulence is one of three broad categories that can be used to classify air flow in the atmosphere, with mean winds and waves being the other two. Stull (1988) also noted that irregular swirls of motion, called eddies, are one way to visualise turbulence, with eddies of many different sizes superimposed on each other typically comprising a turbulence field. In the atmospheric boundary layer (ABL), defined as the lowest layer ($\sim10^2$–10^3 m thickness) of the troposphere that is strongly influenced by surface forcings (e.g. frictional drag due to terrain and vegetation, evaporation and transpiration, surface heat flux (Stull 1988)), the characteristic spatial scales of turbulent eddies range from a few millimetres to the depth of the ABL; their temporal scales range from approximately an hour to less than a second (Orlanski 1975; Stull 1988). With the fairly recent development and advancement of monitoring techniques and sophisticated instrumentation for measuring turbulence in wildland fire environments and in laboratory settings, and the concurrent development of coupled atmosphere, fire behaviour and smoke dispersion numerical modelling tools capable of resolving atmospheric processes at spatial and temporal scales over which turbulence is important, the number of studies focused on turbulence during wildland fires has substantially increased.

Studies of the interactions between atmospheric turbulence and wildland fires have been built on the foundation of many scientific investigations of atmospheric turbulence properties in general that have been conducted over the past 100+ years, as summarised by Counihan (1975), Wyngaard (1992) and Heilman *et al.* (2019*a*). For example, in the early 20th century, studies carried out by Rawson (1913), Shaw (1914) and Richarson (1920) were able to establish some of the very basic principles of flow in the ABL that have guided subsequent turbulence studies since then. Their studies found that boundary layer flow can be turbulent, the energy of turbulent flow usually decreases with height in the ABL, obstructions to atmospheric flow can change the level of randomness in the flow, and the kinetic energy of turbulent eddies is extracted from the kinetic energy of the mean wind. Subsequent foundational turbulence research was conducted by Goldie (1925), Best (1935), Panofsky and McCormick (1954) and Deacon (1955); their studies showed that turbulent eddies near the ground tend to break down into smaller sizes and that turbulence in the ABL is typically anisotropic (i.e. the horizontal and vertical velocities of turbulent eddies tend to be different). Finally, critical theoretical research related to the energetics of atmospheric turbulence was conducted by Taylor (1938) and Kolmogorov (1941). Their theoretical work was instrumental in showing that the energy of turbulent eddies varies with eddy size.

Following these early turbulence studies, a plethora of turbulence-related studies were carried out in the second half of the 20th century and into the 21st century. They not only greatly expanded our understanding of general turbulence characteristics in the ABL, but they also provided benchmark results that have been used in many wildland fire studies for assessing the relative impacts of fires on typical ABL turbulence regimes. Focus areas of these studies included assessments of turbulent heat, momentum and moisture fluxes in the ABL (e.g. Businger *et al.* 1967, 1971; Dyer 1967; Dyer and Hicks 1970; Tillman 1972; Doran *et al.* 1989; Katul *et al.* 1995, 1997, 2006), turbulent kinetic energy (TKE) budgets in the ABL under stable and unstable conditions (e.g. Wyngaard and Coté 1971; McBean and Elliott 1975; Caughey and Wyngaard 1979; Bradley *et al.* 1981; Leclerc *et al.* 1990; Frenzen and Vogel 1992; Dwyer *et al.* 1997; Yang *et al.* 2006; Li *et al.* 2008; Rai *et al.* 2017), the spectral characteristics of turbulent flow and temperature fluctuations under different stability conditions (e.g. Lumley and Panofsky 1964; Berman 1965; Busch and Panofsky 1968; Kaimal *et al.* 1972; Caughey 1977; Wyngaard and Clifford 1977; Baldocchi and Hutchison 1988; Amiro 1990, Liu *et al.* 2001; Högström *et al.* 2002), and the effects of surface vegetation on turbulence properties and turbulent fluxes (e.g. Cowan 1968; Shaw *et al.* 1974, 1988; Wilson and Shaw 1977; Raupach and Thom 1981; Wilson *et al.* 1982; Raupach *et al.* 1986; Baldocchi and Meyers 1988*a*, 1988*b*; Amiro 1990; Meyers and Baldocchi 1991; Shen and Leclerc 1997; Finnigan 2000; Poggi *et al.* 2004; Bohrer *et al.* 2009; Vickers and Thomas 2013).

The quite rapid expansion of ABL turbulence-related studies beginning in the mid-20th century and the realisation at that time that ambient atmospheric turbulence was likely a factor in affecting wildland fire behaviour (Foley 1947; Crosby 1949; Brown 1950; Byram and Nelson 1951) set the stage for many new observational studies of the interactions between turbulence and wildland fires. The present review builds on the Potter (2012*a*, 2012*b*) synthesis effort and provides a summary of the key turbulence-related findings from observational studies that were carried out from 1900 to 2021, including anecdotal turbulence observations, direct turbulence measurements and remote sensing investigations. The review also draws on some of the information presented by Forthofer and Goodrick (2011) in their comprehensive review of studies focused on vortex formation during wildland fire events, a recognition that vortices are an important type of turbulent air flow. Note that the present review does not include a review of past theoretical and modelling studies, which are numerous. They have also contributed substantially to our understanding of atmospheric turbulence interactions with wildland fires, and they merit a focused review of their own.

Anecdotal turbulence observations

As noted in Potter (2012*a*), the most researched aspect of fire–atmosphere interactions is wind. One of the earliest published anecdotal-based references to the connection between wildland fires and atmospheric turbulent flow can be found in Adams (1912), where he notes that fire-induced spiralling updrafts can develop above fires and contribute to the spread of embers. Early 20th century field- and laboratory-based studies attempted to quantify the relationships between wind and fire spread (Show 1919; Curry and Fons 1938; Fons 1946). Although turbulence as a component of the wind field was not explicitly measured in these studies, the study of Show noted that fire-induced indrafts (which are considered turbulent flow) may increase spread rates. More direct discussions of the role that atmospheric turbulence can play in affecting fire behaviour, based primarily on anecdotal observations during wildland fire events, were reported by Crosby (1949), Brown (1950), Byram and Nelson (1951), Graham (1952, 1955, 1957), Byram (1954) and Banks and Little (1964).

In the discussion by Crosby (1949), he noted the gust and lull nature of winds associated with turbulent eddies created by flow over rough surfaces and the potential for those eddies to fan flames in spurts, to move flames in different directions, and to transport heat and embers to surrounding fuels. Turbulent flow in areas of complex terrain, the breakdown of atmospheric inversions that may exist above fire locations due to turbulent plume updrafts, and the acceleration of rising, descending and fire-inflow air currents when inversions above fires break down were noted by Brown (1950) in his essay on warning signs for firefighters. Byram and Nelson (1951) highlighted the generation of fire whirls or vortices (see Forthofer and Goodrick (2011) and Potter (2012*b*) for comprehensive reviews of vortices in wildland fires), a type of coherent turbulent flow (i.e. turbulent eddy), during the 1950 Buckle Island and Farewell wildfires that occurred in the Francis Marion National Forest (South Carolina). They also speculated that unstable turbulent atmospheric layers above these and other wildfires that occurred in the Francis Marion National Forest were a contributing factor to some of the erratic fire behaviour that was observed. Graham (1952, 1955, 1957) reinforced the fire whirl observations of Byram and Nelson (1951) with his reported observations of turbulent fire whirls that were strong enough to damage and break off large trees during wildfire events in complex terrain areas within Oregon in 1951 and 1952. Finally, Banks and Little (1964) noted that turbulent eddies (whirlwinds) were responsible for some of the extreme fire spread rates observed during the April 1963 wildfire that occurred in the New Jersey Pine Barrens.

An early and noteworthy attempt to identify atmospheric wind-speed profiles that could potentially enhance the buoyancy production of turbulence above wildfires and the occurrence of blowup fires was carried out by Byram (1954). Byram used case histories of 17 extreme fires (1939–1953) and available atmospheric sounding data collected within 30–60 miles (48.3–96.6 km) from the recorded fires to come up with six different wind-speed profile classifications as indicative of atmospheric wind regimes that could enhance fire-induced buoyant production of turbulence and increase the likelihood of blowup fires. The presence of a low-level (<2000 feet (610 m) above ground level (AGL)) wind-speed maximum was a common feature of Byram's profile classifications. Although turbulence production due to wind shear above the wind-speed maxima was noted by Byram, the production of turbulence due to wind shear below the maxima and its potential effect on fire behaviour were not discussed at that time.

The early anecdotal observations of turbulence and its impact on wildland fires were followed with questions raised by fire managers as to whether turbulence generated by firefighting aircraft could potentially impact wildland fire behaviour. Davis and Chandler (1965) described how downward propagating turbulent vortices generated by low-flying aircraft and having velocities as high as 40 km h^{-1} can lead to substantial wind gusts near the surface and violent changes in the behaviour of wildland fires occurring in environments with minimal forest overstorey vegetation. More than 20 years later, Haines (1989) recalled the aircraft-generated turbulence concept described by Davis and Chandler in speculating that some of the erratic behaviour of the 1988 Stockyard Fire in Michigan could have been caused by an airtanker flying overhead in support of fire suppression activities.

Direct turbulence measurements

Early photographic analyses

More in-depth analyses of turbulent flow, including fire whirls, during wildland fire events began in the mid-1960s and early 1970s. King (1964) used photographs taken of a fire-induced vortex that developed during the 1962 Dandenong bush fires in Australia (Whittingham 1964) to estimate turbulent vertical velocities within the vortex. Turbulent velocities exceeding 90 m s^{-1} were estimated from the photographic analyses. Pirsko *et al.* (1965) carried out a case study of the 1964 Polo wildfire in southern California during which a destructive whirlwind occurred. They concluded that turbulent fire whirls in regions of complex terrain are more likely to occur under thermally unstable atmospheric conditions and on the lee sides of complex-terrain ridges. Haines and Updike (1971) provided visual evidence of turbulent fire whirl formation during three prescribed fires (1965, 1969, 1970) carried out over flat terrain in Wisconsin and Michigan. As with the Pirsko *et al.* (1965) study, Haines and Updike concluded that turbulent fire whirls are more likely to occur when near-surface atmospheric conditions are thermally unstable (i.e. conditions favourable for enhanced ambient buoyancy production of turbulence). They also concluded that light ambient winds, and thus minimal ambient vertical wind shear, were also favourable conditions for fire whirl formation.

Mass-fire experiments

Complementing these wildland fire studies in the 1960s were two large high-intensity mass-fire experiments conducted in the US and Australia over the 1964–1968 period. The first experiment, known as Project Flambeau (Countryman 1969), and conducted by the USDA Forest Service Pacific Southwest Forest and Range Experiment Station, focused on understanding the behaviour of mass fires (defined as large high-intensity fires by Countryman (1964)). Six experimental burns of different sizes were conducted from 1964 to 1967 in California and Nevada involving multiple and equally spaced (7.6 or 35.1 m) square fuel piles (14.2 m on a side and ~2.1 m thick) arranged in a grid and containing chaparral, fire-killed timber, or pinyon pine–juniper fuels. Custom-designed cup anemometers were installed between the gridded fuel piles in the interior of the plots and at various locations exterior to the plots to measure ambient and fire-induced winds at 6.1 m above ground level. Countryman (1969) analysed the anemometer data collected during the six burns and reported: (1) the occurrence of turbulent fire whirls and dust devils with a peak wind speed of 37.2 m s^{-1} during one of the burn experiments; (2) turbulent inflow along the perimeters of the plots; and (3) the occurrence of turbulent updrafts and downdrafts, with maximum updraft and downdraft velocities of 7.3 and 30.5 m s^{-1}, respectively, during one of the experimental burns. More than a decade later, Palmer (1981) revisited the Project Flambeau atmospheric data collected during the 1964–1967 burn experiments to further explain some of the turbulent flow that occurred. In particular, he noted a zone of intense turbulence and atmospheric mixing near the base of the convection column for one of the six experimental fires due to fire-induced downdrafts adjacent to the convection column that interacted with the near-surface fire-induced horizontal flow into the base of the convection column. Palmer also presented a conceptual model to explain a spiralling turbulent twin-vortex structure that was observed during this particular fire (Fig. 1).

The second mass-fire experiment (also known as the Tumut Fire Experiment) was conducted in 1968 on a 13.2-ha plot in the Bondo State Forest in New South Wales, Australia, during which a variety of physical fire processes, including atmospheric circulations in the vicinity of the fire, were measured (Wilson 1969). Using measurements of wind speed and direction via simple cup anemographs, electrical cup anemometers and a propellor-type anemometer set up along the perimeter and in the interior of the burn plot (2 and 10 m AGL), Wilson (1969) was able to quantify, to some extent, the larger-scale fire-induced convergent and turbulent flow (e.g. wind gusts of 40 m s^{-1}) along the fire perimeter as well as the near-surface turbulent updraft and downdraft variability above the fire. A noteworthy conclusion drawn by Wilson from the measurements was that the turbulent vertical velocity field above the fire was characterised by short periods of strong updrafts interspersed with longer periods of light downdrafts. This finding was an early forerunner of some of the more recent observations of vertical turbulent heat and momentum flux temporal variability above fire fronts using current sonic anemometer technology.

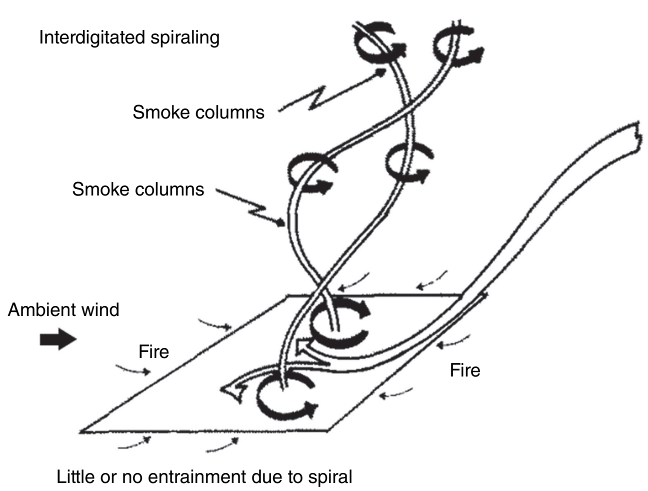

Fig. 1. Conceptual model depicting the fire-generated, interdigitated, spiralling vortex pair in the presence of an ambient wind (left to right) that was observed during one of the Project Flambeau fire experiments (Countryman 1969), with a downdraft jet bringing air from aloft into the bases of the convective columns where atmospheric turbulence was enhanced. Reprinted from Palmer (1981) with permission from Elsevier.

Laboratory fire whirl and fire-spread experiments

Numerous laboratory investigations of turbulent fire whirls were also initiated in the 1960s and 1970s (Byram and Martin 1962; Emmons and Ying 1967; Chigier *et al.* 1970; Beér *et al.* 1971; Lee and Otto 1975; Martin *et al.* 1976; Muraszew *et al.* 1979), which provided more controlled settings for studying fire whirl formation and properties, albeit at spatial scales much smaller than the scales associated with many of the ABL turbulent eddies generated during wildland fire events. The interest in laboratory investigations of turbulent fire whirls has not waned since these early studies, as many more laboratory-based studies were carried out from the 1980s through recent years (e.g. Emori and Saito 1982; Soma and Saito 1991; Snegirev *et al.* 2004; Grishin *et al.* 2005; Akhmetov *et al.* 2007; Chuah and Kushida 2007; Zhou and Wu 2007; Kuwana *et al.* 2008; Chuah *et al.* 2009). Forthofer and Goodrick (2011) summarised the findings from these studies, including the scaling methods used in many of them for extrapolating small-scale (laboratory) fire whirl characteristics to the spatial scales associated with turbulent fire whirls in wildland fire environments.

Of particular note in the suite of laboratory investigations noted above is the Kuwana *et al.* (2008) wind-tunnel study that attempted to reproduce scaled-down versions of three different types of turbulent fire whirls that were observed in the Hifukusho-ato area of Tokyo, Japan, in the aftermath of the 1921 Great Kanto Earthquake (Fig. 2). Numerous open-top pans containing a liquid fuel were configured and ignited within a wind tunnel to mimic the burning environment observed in the Hifukusho-ato area under light airflow (~1 m s^{-1}) conditions. Fire whirl types included whirls that developed over the burning areas (Type 1), whirls that spun off from the burning areas and were transported to downwind and fire flank locations (Type 2), and whirls that developed in non-burning areas as a result of non-fire vortices entraining flames from the adjacent burning areas (Type 3). It is noteworthy that the Type 2 turbulent fire whirls identified in this non-wildland fire study were intimated by Graham (1955) more than five decades earlier in his anecdotal observations of turbulent fire whirls during wildland fire events.

In addition to laboratory investigations of turbulent fire whirls, new laboratory investigations of fire spread and associated buoyant flame dynamics in a turbulent boundary layer have also been carried out. Finney *et al.* (2015) conducted a series of fire-spread experiments inside a wind tunnel containing fuel beds with cardboard fuel elements that were ignited under different wind-speed conditions (0.22–2.3 m s^{-1}). Using high-speed (500 Hz) thermocouple temperature measurements within the fuel beds and imagery of the burning fuel beds obtained from digital video cameras, the investigators provided evidence of complex turbulent (buoyancy-

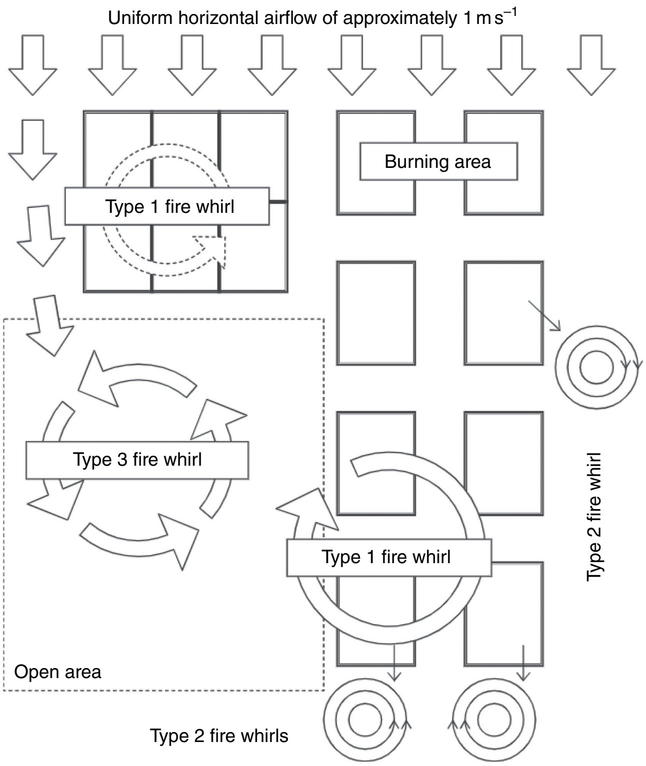

Fig. 2. Schematic of three types of turbulent fire whirls that formed during the Kuwana *et al.* (2008) wind-tunnel investigation of fire whirl formation in the Hifukusho-ato area of Tokyo, Japan, in the aftermath of the 1921 Great Kanto Earthquake. Rectangular boxes depict open-topped pans (eight 30 cm × 41 cm pans on the right side of the figure; six 25 cm × 36 cm pans on the left side of the figure) containing liquid fuel that was ignited. Wind-tunnel horizontal airflow was approximately 1 m s^{-1}. Reprinted from Kuwana *et al.* (2008) with permission from Elsevier.

generated) vortex structures within the flaming zone that can push flames upward and downward and intermittently forward into unignited fuels. The Finney *et al.* (2015) experiments were instrumental in showing how very small spatial- and temporal-scale (~10^{-2} m, ~10^{-1} s) turbulent structures within flaming zones can affect fire spread beyond just the effects of larger-scale (~10^{-1}–100 m, ~1–100 s) ambient and fire-induced turbulent flow found in the ABL.

Investigations of fire-induced turbulent vortex structures in the ABL

The basic mechanisms responsible for the generation of fire whirls and other types of turbulent vortices that were observed and documented during many wildland fire events in the 1900s were investigated and described by Church *et al.* (1980). Using an array of 105 fuel oil burners (total heat output of 1000 MW) set up at the Centre de Recherches Atmosphériques Henri Dessens in Lannemezan, France, turbulent convective plumes under different atmospheric conditions were generated and measured. This study was instrumental in showing how turbulence generation through vertical shear in the horizontal wind near the ground and fire-induced buoyancy can lead to the development of turbulent horizontal roll vortices. The study also demonstrated how turbulence generation through horizontal shear in the horizontal wind, which is often amplified on the downwind flanks of fire fronts, can lead to vertically oriented vortices (i.e. fire whirls).

Turbulent horizontal roll vortices were subsequently investigated quite extensively by atmospheric and fire scientists following the Church *et al.* (1980) groundbreaking effort. Haines (1982) provided observational evidence of unburned tree-crown streets associated with nine crown fires that occurred in the US and Canada, and he hypothesised that turbulent downdrafts associated with horizontal roll vortices were responsible for inhibiting the vertical spread of the wildfires into the crowns. Additional wildland fire observations highlighted in Haines and Smith (1987) led to the identification of three different types of turbulent horizontal roll vortices, with their axes of rotation either parallel or transverse to the ambient wind direction. Smith *et al.* (1986) and Haines and Smith (1992) further assessed horizontal roll vortex development via experiments conducted in a wind tunnel; they were able to observe the formation of horizontal roll vortex pairs above a heated nichrome wire embedded on the floor of the wind tunnel under light wind speeds (~1 m s^{-1}) as well as bent-over (collapsed) vortex pairs in response to turbulence that was introduced into the wind tunnel air flow (Fig. 3). As noted by Haines and Smith (1992), the potential collapse of vortex pairs generated during wildland fire events can threaten firefighting personnel and increase the turbulent transport of firebrands into surrounding fuels.

McRae and Flannigan (1990) and Banta *et al.* (1992) also followed the Church *et al.* (1980) effort with observational studies of turbulent horizontal roll vortices and vertical vortices during prescribed fires and wildfires in Canada and the US. McRae and Flannigan (1990) observed the formation of vertically oriented turbulent whirlwinds on the leeward side of convection columns and turbulent flow associated with entire convection column rotation during prescribed burns conducted in Ontario, Canada. They found that turbulent vortex formation is more likely when fire intensities are high, ambient wind speeds are less than 10 km h^{-1} and ABL lapse rates are generally adiabatic (0.01°C $m^{-1)}$ or superadiabatic (>0.01°C m^{-1}). Banta *et al.* (1992) used Doppler radar and lidar technology to investigate the turbulent flow associated with horizontally and vertically oriented vortices that formed during two forest fires in central Colorado, USA, and northern Ontario, Canada, in 1988. Their remote sensing observations provided direct evidence of extreme vertical velocities (e.g. 10–24 m s^{-1}) within fire-induced turbulent vortices, and further corroborated the extreme vertical velocity evidence provided nearly 30 years earlier by King (1964).

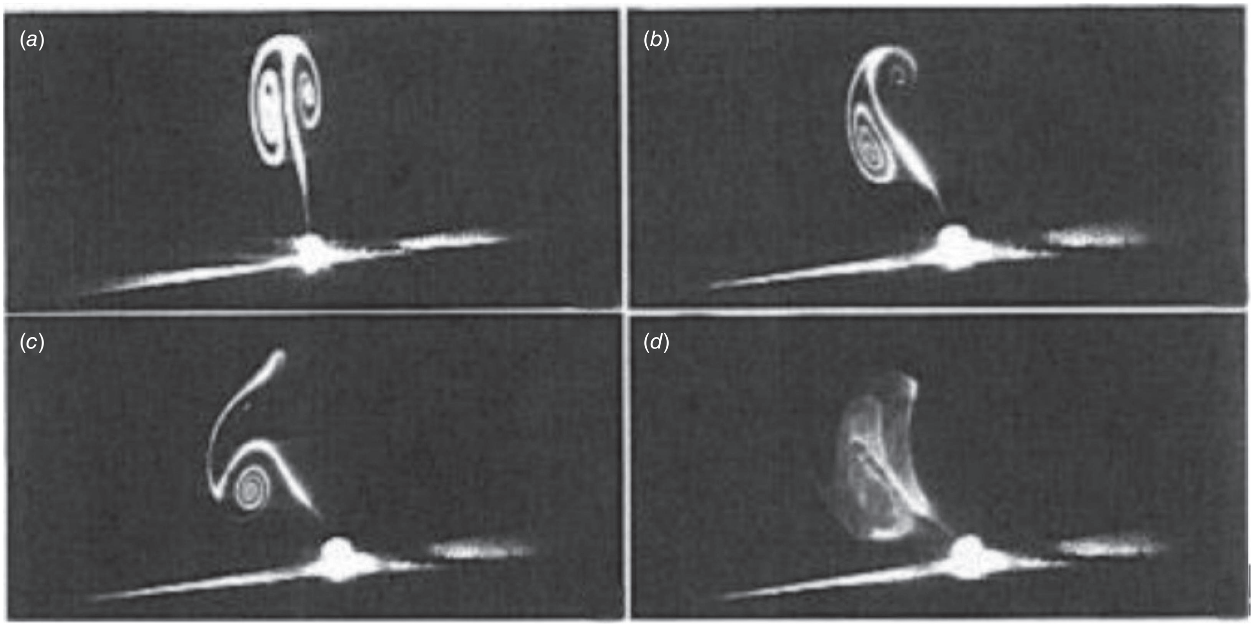

Fig. 3. Photographs of laser-illuminated turbulent vortices in a wind tunnel that developed above a heated nichrome wire (wrapped in silicone with oil absorbed to generate smoke) running down the centreline of the wind tunnel under weak (1.0–1.5 m s^{-1}) mean wind speeds and different turbulent cross-flow circulations, as reported in the study of Haines and Smith (1992). Varying levels of turbulent cross-flow were generated by placing a 45° delta wing upwind of the nichrome wire and 1 cm off the tunnel centreline, while orienting the wing (*a*) parallel to, (*b*) 3° off, (*c*) 6° off, and (*d*) 9° off the direction of the mean wind. Reproduced from Haines and Smith (1992) by permission of Oxford University Press.

Turbulence measurements during large field campaigns

The last decade of the 20th century ushered in a new era of large field campaigns to measure fire–fuel–atmosphere interactions during wildland fire events, with many of them involving direct turbulence regime measurements within and near the fire environment. The International Crown Fire Modelling Experiment (ICFME) (Stocks *et al.* 2004) conducted near Fort Providence, Northwest Territories, Canada, over the 1995–2001 period utilised tower-based anemometer measurements (0.2 Hz) of wind speed and direction along the perimeters of active burning plots (150 m per side) containing jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* (Mill.) BSP) to explore connections between crown-fire spread and wind variability (Taylor *et al.* 2004). The anemometer measurements revealed that fire spread variations observed during the experiment were consistent with the influence of turbulent coherent wind gusts. A more in-depth analysis of the atmospheric turbulence regimes that developed during a subset of the ICFME experimental burns using infrared (IR) imagery was carried out by Clark *et al.* (1999). Infrared imagery obtained during a burn conducted on 9 July 1997 revealed that highly energetic turbulent eddies with spatial scales of the order of a few metres were generated by the fire, and they led to substantial wind-speed variations occurring over fractions of a second.

The Wildfire Experiment (WiFE) project (Radke *et al.* 2000) incorporated airborne sensors (high-speed IR camera, multispectral visible-IR line scanner, microwave radiometer) to detect horizontally and vertically oriented turbulent vortices during wildfire events in Montana and California in 1998. Turbulent wind speeds of the order of 20 m s^{-1} were observed within these vortices.

Finally, the 1999 FROSTFIRE Experiment (Coen *et al.* 2004) conducted in Alaska made significant inroads in showing how fire-induced turbulence can actually affect fire spread. Using IR imaging technology and a sophisticated image flow analysis technique, investigators were able to derive the circulation patterns that developed in and near high-intensity crown fires that propagated up a slope (~20°) under light ambient wind speeds (3 m s^{-1}). The analyses revealed maximum turbulent updraft and downdraft wind speeds of 60 and 30 m s^{-1}, respectively, as well as maximum fire-induced inflow into the base of the convective updrafts of 28 m s^{-1} (Fig. 4). More complex turbulent flow that led to flaming fingers moving rapidly upslope at speeds up to 48 m s^{-1}, much faster than the mean ambient wind speed, were also identified in the analyses.

In situ turbulence measurements: flat terrain

Following the ICFME, WiFE and FROSTFIRE major field campaigns in the late 1990s, many field investigations of atmospheric turbulence and its role in fire–fuel–atmosphere

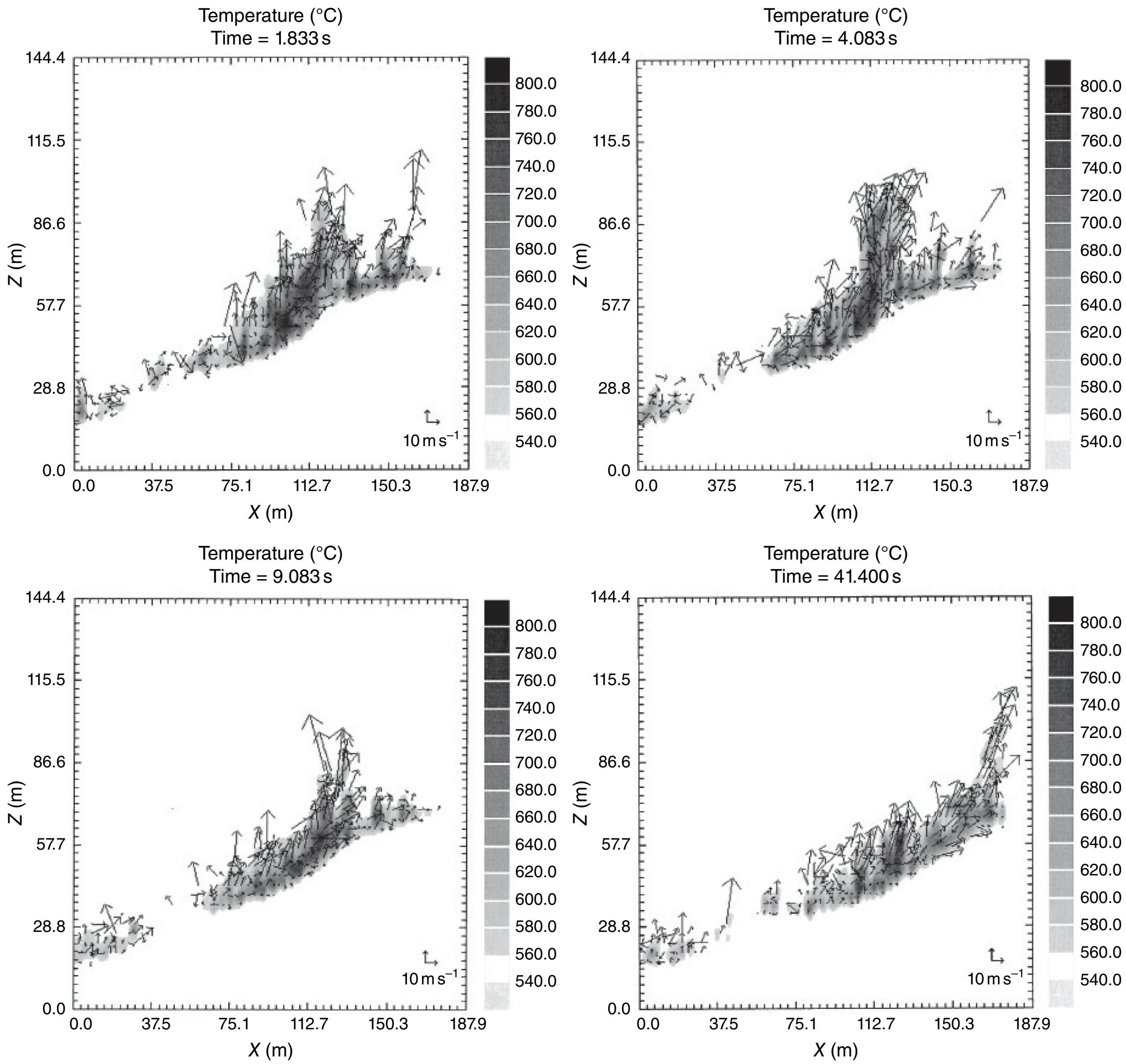

Fig. 4. Vertical cross-sections of a sequence of images from an image-flow analysis of instantaneous temperatures (°C: grey scale) and velocities (m s^{-1}: vectors) within the combustion zone of a crown fire spreading upslope (left to right) during the FROSTFIRE experiment conducted on 9–10 July 1999 in Alaska (Coen *et al.* 2004). Reproduced from Coen *et al.* (2004), ©American Meteorological Society. Used with permission.

interactions in the early decades of the 21st century focused on *in situ* measurements during fire events in forested, grassland and complex terrain environments. The first comprehensive wildland fire experiment in the US to incorporate *in situ*, high-frequency, tower-based measurements of turbulent flow associated with a wind-driven (heading) grassfire was the 2006 FireFlux 1 experiment conducted by Clements *et al.* (2007) at the Houston Coastal Center in Texas. The experiment spawned a second comprehensive grassfire experiment at the same site in 2013 (FireFlux 2, Clements *et al.* 2019) along with follow-up studies that investigated the statistics, energetics and heat/momentum flux mechanisms associated with ambient and fire-induced turbulent flow that can occur before, during and after fire-front passage.

In one of the studies, Clements *et al.* (2008) found that the energy of the turbulent flow (i.e. turbulent kinetic energy, TKE) generated by the FireFlux 1 heading grassfire was of the order of five times greater than the ambient TKE at heights just above the fire front (2 m), with the energy differences decreasing with height (10 $m^2 s^{-2}$ vs 2 $m^2 s^{-2}$ at 2 m AGL; 5 $m^2 s^{-2}$ vs 2 $m^2 s^{-2}$ at 42 m AGL) (Fig. 5*a*). Turbulent kinetic energy associated with horizontal velocity fluctuations substantially exceeded the TKE associated with

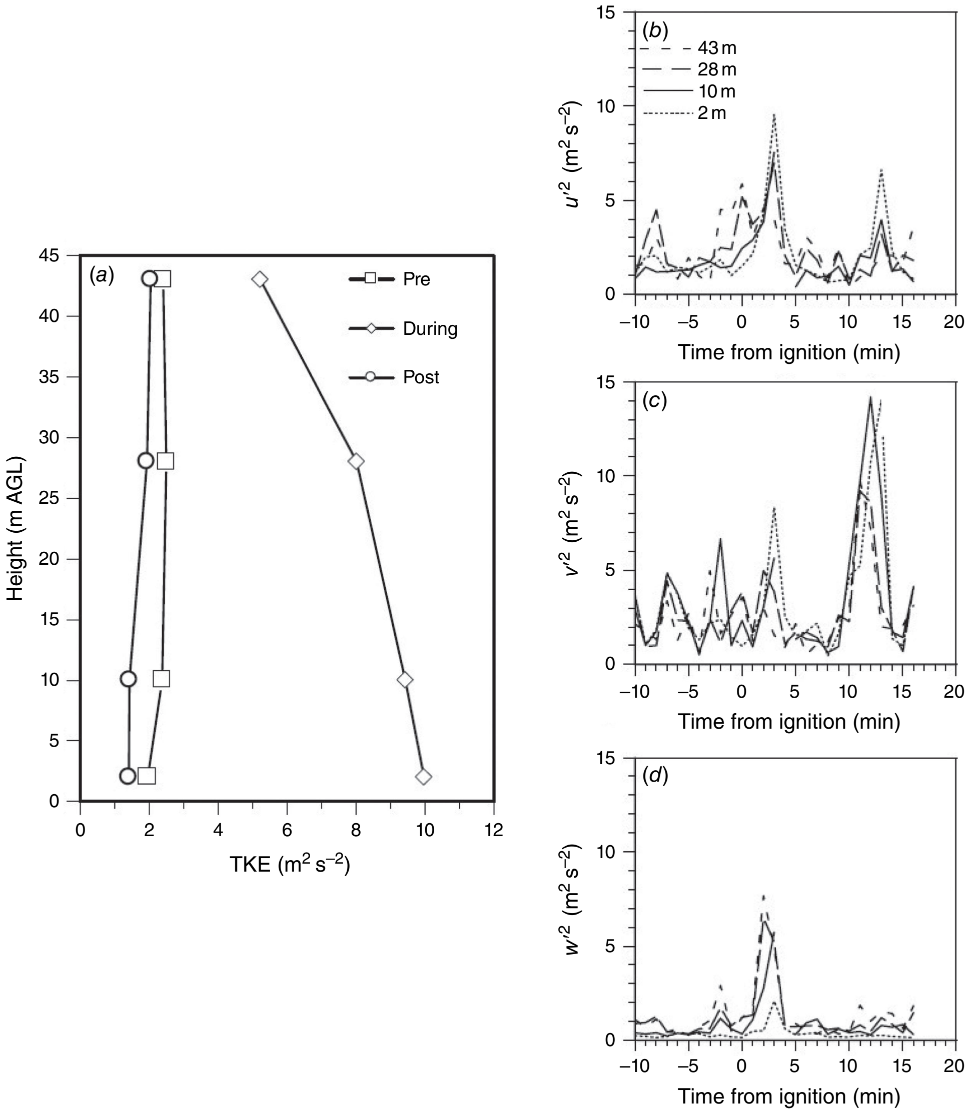

Fig. 5. Tower-based observations of (*a*) turbulent kinetic energy (TKE) vertical profiles before (pre), during, and after (post) fire-front passage, and time series of the TKE components represented by (*b*) the horizontal east–west velocity variance (u'^2), (*c*) the horizontal north–south velocity variance (v'^2), and (*d*) the vertical velocity variance (w'^2) during the 2006 FireFlux I grassfire experiment in Texas (Clements *et al.* 2008). Adapted from Clements *et al.* (2008) by permission from the American Geophysical Union.

vertical velocity fluctuations just above the fire front (2 m), an indication of turbulence anisotropy at that level (Fig. 5*b*–*d*). The anisotropy decreased with height in response to enhanced vertical velocity fluctuations at higher levels above the fire front. Finally, spectral analyses of the vertical velocities recorded above the fire front were instrumental in showing that the increase in TKE during periods of fire-front passage is primarily due to large rather than small fire-induced turbulent eddies.

A second follow-up study of the FireFlux 1 experiment was carried out by Clements (2010) where the thermal structure of the FireFlux 1 convective plume was examined. Tower-based thermocouple measurements of plume temperatures revealed regions of entrainment of ambient air near the top of the convective plume and on the underside of the plume downwind of the fire front. It was noted that the entrainment of ambient air into the underside of the plume was likely caused by the presence of a turbulent horizontal roll vortex ahead of the fire front as well as the turbulent inflow into the approaching fire front.

The previously discussed laboratory-based study of fire spread and flame dynamics conducted by Finney *et al.* (2015) set the stage for a series of wildland fire experiments carried out by Katurji *et al.* (2021) in flat stubble wheat-field plots located in Darfield, New Zealand, in 2018, as summarised by Finney *et al.* (2018). The Katurji *et al.* (2021) study utilised *in situ* instrumentation (sonic anemometers and thermocouples) and remote sensing instrumentation (IR camera) to measure both the small-scale flaming-zone turbulent dynamics and the larger-scale fire-induced turbulent flow that can interact with the flaming-zone turbulence regimes. The study was successful not only in highlighting the merits of using longwave IR imagery and associated imagery analysis techniques (e.g. thermal image velocimetry (Inagaki *et al.* 2013) and image segmentation (Najman and Schmitt

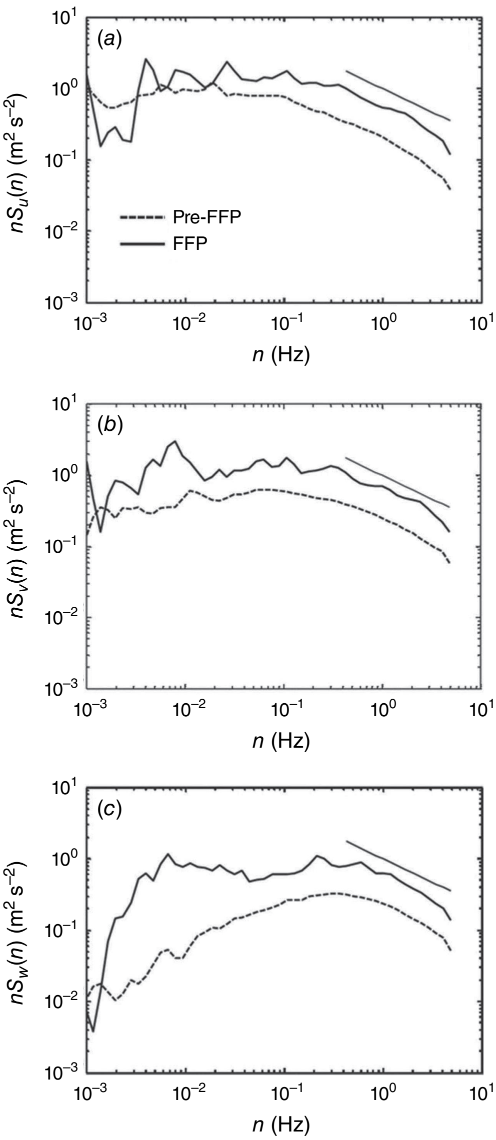

Fig. 6. Non-normalised, frequency-weighted power spectra of the (*a*) streamwise wind velocity $nS_u(n)$, (*b*) crosswise wind velocity $nS_v(n)$, and (*c*) vertical wind velocity $nS_w(n)$ as a function of the natural frequency n at 11 m above ground level before (pre-FFP) and during (FFP) the passage of the fire front during the 2010 Grass Fires on Slope Experiment (Seto *et al.* 2013). The short line represents the −2/3 slope of power spectra predicted from classical turbulence theory (Kolmogorov 1941). Reprinted from Seto *et al.* (2013) with permission from Elsevier.

1994)) to examine the turbulent movement of hot air within and near fire fronts, but also in providing strong evidence of interactions that can occur between small-scale turbulence in the flaming zone and larger-scale ambient and fire-induced turbulent flow in the lower ABL. Specifically, the inertial-subrange spectral characteristics of the turbulent movement of hot air within the fire fronts were found to be similar to the inertial-subrange spectral characteristics of the turbulent flow above the fire fronts.

Finally, Heilman *et al.* (2021*a*) reexamined the FireFlux 1 data to assess the turbulent heat and momentum flux sweep-ejection dynamics (Katul *et al.* 1997) that occurred before, during and after fire-front passage during the experiment. The study showed that a heading grassfire can create an environment dominated by turbulent heat-flux ejection events that transport heat upward and away from the surface via turbulent updrafts, in contrast to non-fire grassland environments where ejection and sweep events (i.e. the downward turbulent transport of cool air from above) tend to equally dominate during the daytime. For turbulent momentum fluxes, the study showed that downward turbulent transport of high-momentum air from above (sweep events) can be the most significant contributor to mean momentum fluxes just above fire fronts, even though buoyant updrafts are strong.

In situ turbulence measurement: complex terrain

As noted in Werth *et al.* (2011), Sharples (2009) and Sharples *et al.* (2012), terrain-induced atmospheric turbulence and its interaction with fire-induced turbulence was recognised at that time as an important causal factor in extreme fire behaviour occurrences in areas of complex terrain. With that backdrop in mind, investigations of fire-induced turbulence regimes using *in situ* monitoring techniques expanded to areas of complex terrain following the FireFlux 1 experiment. Seto and Clements (2011) observed turbulent fire whirl formation during a 2008 prescribed fire in a narrow valley within the Diablo Range in California and ~60 km east of the Pacific Ocean. They showed how sea breezes, thermally driven up-valley winds and fire-induced circulations can interact and lead to strong vertical wind shears conducive to turbulence generation and fire whirl formation.

In 2010, the Grass Fires on Slope Experiment was conducted near Dublin, California (Seto *et al.* 2013; Clements and Seto 2015). This experiment involved multiple ignition lines (backing and heading) on a slope that were allowed to spread across and up the slope in response to ambient cross-slope winds and fire-induced winds, with *in situ* tower instrumentation providing measurements of ambient and fire-induced turbulent flow. Observations showed that fires can increase high-frequency velocity and temperature fluctuations (Fig. 6), an indication that the kinetic energy of small turbulent eddies can also be enhanced during fire-front-passage periods, just like the energy of large eddies as noted in the previously discussed Clements *et al.* (2008) study. Observations also showed maximum turbulence anisotropy immediately above the fire front and a more isotropic turbulence environment at higher elevations above the fire front, a finding that reaffirmed previous observations from the 2006 FireFlux 1 experiment.

In 2011, Charland and Clements (2013) conducted a backing downslope prescribed grassfire experiment near

San Jose, CA. Turbulent flow leading to convergence at the base of the convective column as the fire front moved downslope was identified using *in situ* instrumentation complemented with Doppler lidar measurements. Another prescribed grassfire experiment conducted in 2012 on a simple slope (with *in situ* instrumentation) located at Fort Hunter Liggett in central CA (Arreola Amaya and Clements 2020) provided further evidence that atmospheric turbulence regimes above fire fronts tend to be anisotropic, with most of the turbulent energy associated with fluctuations in the horizontal winds.

In situ turbulence measurements: forested environments

Many observational investigations of atmospheric turbulence regimes that develop during wildland fires in forested environments were also initiated in the early 21st century, drawing on much of the previously conducted foundational research of vegetation impacts on atmospheric turbulence as noted in the Introduction. In 2008, 2011 and 2012, a suite of low-intensity prescribed fire experiments in forested and non-forested environments were conducted in the southeastern US as part of the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) (Ottmar *et al.* 2016). A wide array of fuel, meteorological (including turbulence), fire behaviour, emissions and fire effects measurements were made during the experiments. Based on the fire behaviour measurements and the *in situ* and Doppler lidar atmospheric measurements made during the 2012 RxCADRE fire experiments, Clements *et al.* (2016) concluded that even low-intensity fires (including those in forested environments) can lead to atmospheric flow perturbations that can feed back on fire-front behaviour.

Concerns about adverse local air quality during low-intensity wildland fires in forested environments prompted the US Joint Fire Science Program to fund a series of prescribed fire experiments from 2010 to 2012 in New Jersey and North Carolina focused on smoke plume dynamics and the effects of ambient and fire- and canopy-induced atmospheric turbulence on local smoke dispersion (Heilman *et al.* 2013; Strand *et al.* 2013). *In situ* tower-based measurements of turbulent flow from near the surface to canopy tops during the experiments provided insight into the typical turbulence regimes that develop above low-intensity surface fire fronts in forested environments. Analyses of the data collected from these experiments led to the following conclusions: (1) maximum increases in turbulent energy due to surface fires can occur near the top of the canopy as opposed to just above the front (Heilman *et al.* 2015), thereby enhancing smoke dispersion there; (2) fire-induced turbulent downdrafts can transport cooler air from aloft downward through forest vegetation layers to near the surface such that fire behaviour and local smoke dispersion may be affected (Seto *et al.* 2014; Heilman *et al.* 2015); (3) the horizontal turbulent mixing of smoke during low-intensity fires generally exceeds vertical mixing near the surface and just above canopy tops (Heilman *et al.* 2015, 2017); (4) both buoyancy and vertical wind shears contribute substantially to the production of turbulent energy in the vicinity of advancing fire fronts in forested environments (Heilman *et al.* 2017); (5) turbulent horizontal and vertical velocity distributions tend to be highly skewed during the passage of fire fronts such that assumptions of Gaussian turbulence regimes in smoke dispersion modelling systems may not be valid (Heilman *et al.* 2017); (6) horizontal turbulent heat fluxes tend to exceed vertical fluxes above surface fire fronts in forested environments, whereas the opposite tends to occur with turbulent momentum fluxes (Heilman *et al.* 2019*b*); and (7) the downward turbulent transfer of high-momentum air from aloft (also known as sweep events) into the combustion zones of wildland fires in forested environments can be substantial (Fig. 7) (Heilman *et al.* 2021*a*).

An assessment of the potential connections between fuel consumption, fire behaviour, atmospheric turbulence and energy exchange was carried out by Clark *et al.* (2020) using data collected from *in situ* instrumentation set up during eight low- and high-intensity (both backing and heading) prescribed fires in the forested New Jersey Pinelands National Reserve over the 2006–2015 period. This assessment found that high-intensity heading fires can lead to enhanced turbulent transfer of smoke and enhanced production and turbulent transport of firebrands. However, the study also found that the consumption of surface and understorey fuels was not significantly correlated with the level of buoyant heating or any turbulence statistic for the particular fires that were examined. Instead, it was concluded that longer residence times of fire fronts during low-intensity backing fires is what makes them effective in reducing surface and understorey fuels.

Finally, *in situ* atmospheric turbulence measurements were a prominent feature of a series of prescribed fire experiments in 2018 and 2019, also conducted in the New Jersey Pinelands National Reserve, that focused on wildland fire combustion processes in open-canopied forests (Skowronski *et al.* 2021). Near-surface and tower-based sonic anemometers set up within prescribed burn plots were used to measure the temporal and spatial variations in turbulent flow above and in the vicinity of surface fire fronts as they progressed through the plots. While reaffirming many of the fire-induced turbulence regime characteristics that were identified in previous wildland fire experiments conducted in the Pinelands National Reserve, the 2018 and 2019 experiments also were instrumental in showing that turbulent momentum fluxes above fire fronts in forested environments can exhibit periodicity patterns at temporal scales consistent with the temporal variability observed in the spread of some fire fronts (Heilman *et al.* 2021*b*).

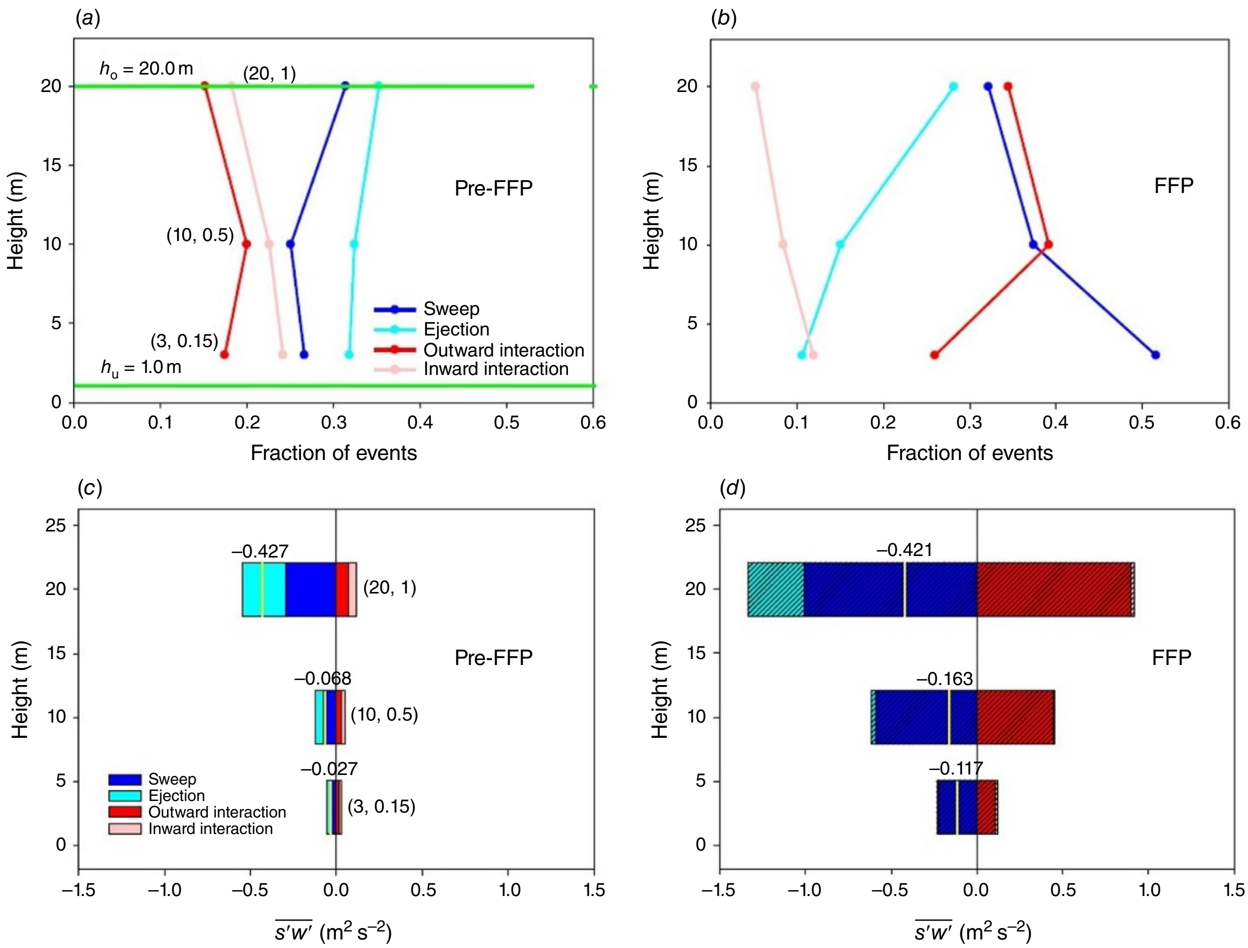

Fig. 7. Vertical profiles of the fractional number of sweep (downward flux of high-horizontal-momentum air from above), ejection (upward flux of low-horizontal-momentum air from below), outward interaction (upward flux of high-horizontal-momentum air from below), and inward interaction (downward flux of low-horizontal-momentum air from above) events (*a*) before (pre-FFP), and (*b*) during (FFP) fire-front passage; and the event contributions to the mean turbulent momentum fluxes ($\overline{s'w'}$) at each height (*c*) before, and (*d*) during fire-front passage during a 2011 New Jersey Pine Barrens fire experiment (Heilman *et al.* 2013). In (*a*), green lines indicate average understorey h_u or overstorey h_o vegetation height, and numbers in parentheses represent the (z/h_u, z/h_o) relative heights (z = height above ground level). In (*c, d*), striped bars indicate statistically significant variations ($P < 0.01$) from the pre-FFP mean values. The mean turbulent momentum flux at each height level is depicted by the yellow vertical lines and the associated numerical values (m^2 s^{-2}) above the lines; bold face numbers indicate statistically significant variations ($P < 0.01$) from the pre-FPP mean values. Adapted from Heilman *et al.* (2021*a*), © American Meteorological Society. Used with permission.

Remote sensing of turbulent plume dynamics

Efforts to examine fire-induced turbulence regimes using *in situ* instrumentation in the early 21st century were complemented with new remote sensing measurements of wildland fire plume dynamics (including turbulence effects), utilising near-infrared lidar technology that was previously shown to be a viable means of measuring smoke plumes and plume dispersion (e.g. Benech *et al.* 1988; Banta *et al.* 1992; Kovalev *et al.* 2005; Hiscox *et al.* 2006). In addition to the previously mentioned Doppler lidar measurements carried out during the 2011 prescribed grassfire experiment near San Jose, CA (Charland and Clements 2013), and the 2012 RxCADRE experiment (Clements *et al.* 2016), Lareau and Clements (2015) used a Doppler lidar system to measure smoke-induced density currents during the 2014 Bald and Eiler wildfires in California and concluded from the measurements that density currents can lead to rapid wind shifts (i.e. turbulent flow) in the ABL and potential changes in wildland fire behaviour. Doppler lidar measurements of smoke plumes were also carried out by Lareau and Clements (2017) during the 2014 El Portal wildfire in California. These measurements were instrumental in showing that within-plume turbulent eddies with spatial scales of the order of 100 m can substantially contribute to turbulent mixing of

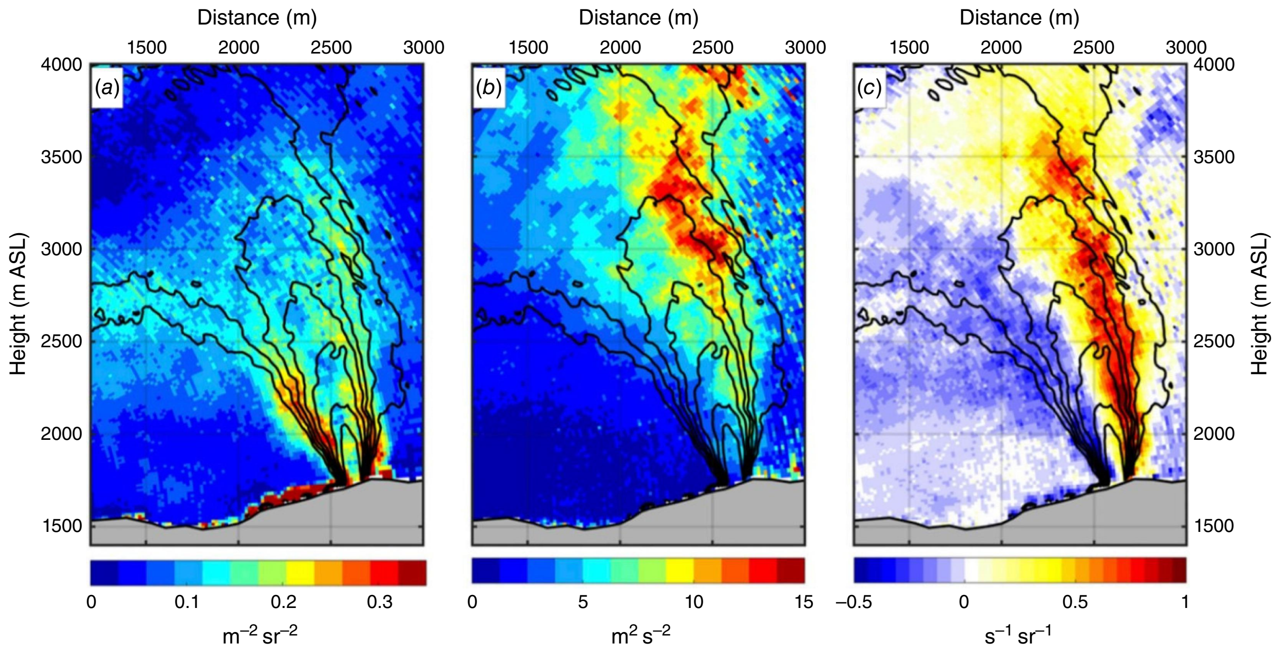

Fig. 8. Doppler Lidar measurements of turbulent variations in the plume structure associated with the 2014 El Portal wildfire in California (Lareau and Clements 2017): (*a*) variance of the smoke backscatter; (*b*) variance of the radial velocity; and (*c*) covariance of the smoke backscatter and radial velocity. The mean backscatter is also shown (black contours, with a contour interval of 0.25 m^{-1} sr^{-1}). Reproduced from Lareau and Clements (2017), © American Meteorological Society. Used with permission.

wildland fire plumes at their boundaries, thereby diluting plume concentrations (Fig. 8).

Remote sensing studies of wildland fire plumes using radar technology have also been carried out in the early 21st century. Many of these studies focused on pyro-cumulonimbus development and structure during wildfire events (e.g. Fromm *et al.* 2006, 2012; Rosenfeld *et al.* 2007; Lareau and Clements 2016; Dowdy *et al.* 2017; LaRoche and Lang 2017; Ndalila *et al.* 2020), the vertical extent to which burnt debris can be lofted into the atmosphere and subsequently transported during wildfire events (e.g. Jones and Christopher 2009, 2010*a*, 2010*b*; Price *et al.* 2018; Li *et al.* 2019; McCarthy *et al.* 2020), linking properties of radar-observed plumes to fire behaviour (e.g. Hanley *et al.* 2013; McRae *et al.* 2015; Duff *et al.* 2018) and characterising plume particles (e.g. Melnikov *et al.* 2008). Complementing these studies were additional efforts to apply radar technology to further our understanding of the turbulent flow associated with wildland fire plumes, an application concept suggested and explored in the late 1960s and early 1970s by Lhermitte (1969) and Reid and Vines (1972). A comprehensive review of how radar has been used to study wildland fires can be found in McCarthy *et al.* (2019), and some of the key radar-based turbulence-focused studies carried out in the early 21st century are noted in the discussion below.

Fromm *et al.* (2006) and McRae *et al.* (2013) highlighted the radar tracking (non-Doppler, Australian Bureau of Meteorology) of a tornado spawned from a pyro-cumulonimbus plume that developed during the bushfires of 18 January 2003 near and within the city limits of Canberra, Australia. Although the non-Doppler radar data did not provide a means of quantifying the turbulent winds associated with the tornado, the radar reflectivity was consistent and correlated with areas where extensive damage to homes, vehicles and vegetation occurred as a result of the turbulent winds.

The recent application of Doppler radar technology for investigating atmospheric environments during wildland fire events has resulted in substantial advancements in our understanding of how turbulent flow can influence fire behaviour and smoke dispersion. For example, Murdoch *et al.* (2016) used imagery and data from the National Weather Service's WSR-88D (https://www.weather.gov/iwx/wsr_88d) Doppler radar located in Granger, Texas, during the destructive Bastrop Complex wildfire in 2011 to show how the alignment of ambient turbulent horizontal longitudinal vortices in the ABL with the horizontal roll vortices generated by the fire likely resulted in enhanced turbulent downdrafts and combustion along the flank of the fire.

Doppler radar imagery incorporated by Peace *et al.* (2017) into their case study of the 2016 Waroona bushfire in Western Australia, which burned an area of more than 69 000 ha (McCaw *et al.* 2016), was critical in showing not only the structure of the pyro-cumulonimbus and associated turbulent downdrafts that formed during the event, but also the presence of terrain-induced (turbulent downslope flow) and fire-induced wind convergence zones in the vicinity of the fire. It was concluded that the turbulent flow associated with the convergence zones was likely responsible for an ember shower with mass spotting and extreme fire behaviour that was observed during the fire event.

Lareau *et al.* (2018) provided a compelling Doppler radar-based analysis of the causes of the turbulent vortex circulations that developed during the devastating 2018 Carr wildfire in California (~92 000 ha burned) when it spread into the western suburbs of Redding on 26 July. The analysis revealed how turbulence generation and associated vertical vorticity development due to horizontal wind shear (brought on by terrain variability and fire-modified winds) were further enhanced by the rapid vertical development of the convective plume above the fire. The radar analysis also revealed the substantial vertical growth of the turbulent vortex, which reached the base (~5500–6000 m AGL) of the pyro-cumulonimbus that formed on 26 July. A vortex maximum gate-to-gate horizontal wind shear of $\sim 37\ \mathrm{m\ s^{-1}}$, corresponding to a maximum vortex rotational wind speed of $\sim 18.5\ \mathrm{m\ s^{-1}}$, was derived from the radar data, although these values were considerably less than the $\sim 64\ \mathrm{m\ s^{-1}}$ vortex wind speeds estimated by the National Weather Service (Lareau *et al.* 2018).

Rodriguez *et al.* (2020) used the Wyoming Cloud Radar (WCR) system, a Doppler-based radar system mounted in an aircraft, to measure turbulent updraft and downdraft speeds during a period of rapid plume growth above the 2016 Pioneer Fire in Idaho, a major wildfire that burned a total of 76 081 ha. The measurements revealed the extreme turbulent flow speeds that are possible in the convective plumes above extreme wildfires, with maximum updraft speeds reaching nearly $60\ \mathrm{m\ s^{-1}}$ in the plume core at heights between 4 and 6 km above the surface during this particular fire. Maximum downdraft speeds of nearly $30\ \mathrm{m\ s^{-1}}$ were observed along the periphery of the plume. The updraft speeds observed during this fire were similar to the updraft speeds that have been observed within tornadic supercell thunderstorms.

Finally, a new high-resolution mobile Doppler radar system (operational wavelength of 1 mm as opposed to ~10-cm wavelength of most radar systems) capable of measuring the fine-scale kinematics and micro-physical regimes within wildland fire plumes was utilised by Aydell and Clements (2021) to examine turbulent flow within and adjacent to convective plumes. Radar measurements were made during the 2019 Kincade and Briceburg wildfires in California and during a 2019 prescribed fire conducted in Utah as part of the Fire and Smoke Model Evaluation Experiment (FASMEE) (Prichard *et al.* 2019). During the Kincade wildfire, Doppler radar scans were able to identify a convergence zone associated with turbulent flow generated by the fire nearly 1 km downwind of the base of the convective plume. Highly turbulent flow within and just upwind of the convective plume core of the Kincade wildfire was also identified via Doppler spectrum width analyses.

Summary and conclusions

This summary of the key observational studies carried out over the last 120 years on atmospheric turbulence regimes during wildland fire events highlights the substantial advancements that have been made in our understanding of how fire-induced and ambient turbulent flow can affect fire behaviour and smoke plume dynamics (see Fig. 9). From the early anecdotal observations of smoke plume behaviour above fires and its attribution to variable air flow within the plumes to recent comprehensive and sophisticated *in situ* and remote sensing measurements of turbulent flow in the fire environment and convective plumes, our knowledge of the connections between wildland fires and turbulence has expanded greatly. Throughout this period, investigations of the properties of atmospheric turbulence regimes conducive to or induced by wildland fires have been guided by and have drawn from many foundational studies of ambient ABL turbulence in non-fire environments. Most notable in the earlier studies was a recognition that turbulence generation (manifested as wind gusts and lulls) due to vertical shear in the ambient horizontal winds (often prevalent in areas of complex terrain) and buoyancy can contribute to variable or erratic fire behaviour. This recognition helped pave the way for subsequent investigations of the connections between ambient turbulence regimes and fire behaviour.

From a spatial perspective, many of the highlighted observational studies have shed light on where turbulent flow is likely to occur (and its strength) within and in the vicinity of convective plumes above wildland fires as well as upwind and downwind of active burning and smouldering areas. Turbulent vortices have been a substantial focus of these studies. Through laboratory experiments, controlled burn experiments and *in situ* and remote sensing measurements during actual wildland fire events, investigators have been able to identify different types of fire-induced horizontally and vertically oriented turbulent vortex structures and their spatial evolution. Some of the experiments were able not only to show that vertical shear in the horizontal wind field plays a role in turbulent vortex development, but also that horizontal shear in the horizontal winds (ambient and fire-induced) can lead to vertically oriented turbulent vortices (i.e. fire whirls) at preferred locations (e.g. downwind flanks of fire fronts).

In addition to studies that focused on where turbulent vortices are likely to develop, other studies have focused on spatial variations in turbulence regimes above surface fire fronts, including fire fronts within forested environments. Of particular importance for smoke dispersion and its prediction during fire events in forested regions, studies have revealed that the energy of turbulent flow (and thus the turbulent mixing of smoke plumes) above fire fronts is often at a maximum near the top of forest canopies.

From a temporal perspective, *in situ* measurements of turbulent flow within and in the vicinity of wildland fire

Anecdotal turbulence observations (1900–1965)

Fire-induced updrafts
Turbulent eddies fanning flames
Turbulent airflow over complex terrain
Breakdown of inversions due to turbulent updrafts
Fire-induced inflow
Turbulent fire whirls/vortices
Wind speed profiles that enhance buoyancy production of turbulence
Turbulence generation via firefighting aircraft

Direct turbulence measurements (1960–2021)

Photographic analyses
- Turbulent wind speeds in fire vortices
- Fire-whirl formation over flat/complex terrain

Mass fire experiments
- Fire-whirl formation
- Turbulent updrafts/downdrafts
- Turbulence at base of convection column
- Wind gusts along fire perimeters

Laboratory experiments
- Fire-whirl formation
- Formation of complex turbulent vortex structures
- Connections between small-scale turbulent structures and fire spread
- Turbulent horizontal roll vortices

In-situ measurements
- Connections between crown-fire spread and wind variability
- Turbulent vortices
- Turbulent updrafts/downdrafts
- Skewness of turbulent velocity distributions
- Turbulence production and energetics
- Turbulent heat/momentum fluxes
- Turbulence anisotropy
- Turbulent entrainment of ambient air into convective plumes
- Sweep-ejection dynamics
- Turbulence spectra
- Canopy and terrain effects on fire-induced turbulence
- Connections between turbulence, fuel consumption, fire behaviour, and energy exchange

Remote sensing measurements (1988–2021)

Fire-induced flow perturbations and their feedback on fire behaviour
Turbulent flow convergence upwind, downwind, and at base of fire-induced convective columns
Airflow variability due to smoke-induced density currents
Convective-plume turbulent eddies and plume entrainment
Pyro-cumulonimbus development
Vertical turbulent transport of burnt debris
Interactions of ambient turbulent vortices with fire-induced horizontal roll vortices
Fire-induced wind convergence zones
Fire-induced turbulent updrafts, downdrafts, and vortices

Fig. 9. Summary of turbulence properties and processes in wildland fire environments that have been observed and measured via studies conducted and reported over the 1900–2021 period.

fronts in flat-terrain, complex-terrain, grassland and forested environments that have been carried out over the last 20 years have been instrumental in showing how fires can affect the temporal variability of near-surface and lower boundary-layer winds. It is through that observed temporal variability that we are now able to assess how wildland fires generate turbulent eddies of different sizes, how the energy of turbulent eddies in the fire environment varies from large (~100 m) to small (~1 m or less) eddy sizes, and how fires affect the transfer of turbulence energy from large to small eddies, which eventually dissipate. Furthermore, *in situ* measurements have revealed how vertical turbulent fluxes of momentum and heat temporally vary above and near fire fronts, which are key processes that affect fire behaviour and plume dynamics.

Advancements that have been made in our understanding of atmospheric turbulence regimes in wildland fire environments come with a recognition that knowledge gaps still remain. For example, *in situ* measurements of turbulent flow during wildland fire events have, for the most part, been limited to low-intensity fires that allow monitoring without excessive instrument degradation or failure. The properties and characteristics of local atmospheric turbulence regimes induced by high-intensity wildland fires, including crown fires, and their feedback on fire behaviour are not well understood yet because of the limitations in trying to do *in situ* monitoring during high-intensity fire events. Specifically, turbulence properties and processes such as turbulence anisotropy, heat- and momentum-flux sweep-ejection dynamics, horizontal and vertical diffusion of heat and momentum, TKE budgets and the spectral characteristics of turbulent flow in high-intensity wildland fire environments are knowledge gaps that still confront the fire science community.

Many of the knowledge gaps that exist in relation to turbulence regimes during high-intensity fire events also exist for nocturnal fire events. Past observational studies of atmospheric turbulence in the vicinity of fire fronts and within convective plumes above fire fronts have been carried out almost exclusively during the daytime under thermally neutral or unstable ambient conditions in the ABL. The development of thermally stable nocturnal inversion layers during wildland fire events that burn through the night-time hours can potentially lead to very different fire-induced turbulence regimes and interactions with the stable ambient environment, thereby affecting fire behaviour and smoke dispersion. New observational studies during nocturnal wildland fire events are needed to examine the same turbulence properties and processes previously noted for high-intensity fires.

Although a few *in situ* monitoring efforts have included measurements of pressure variations in the vicinity of fire fronts (e.g. Clements *et al.* 2019; Skowronski *et al.* 2021), the extent to which vertical and horizontal gradients of turbulent pressure fluxes (also known as the pressure redistribution or the return-to-turbulence-isotropy effect; Stull (1988); Wei *et al.* (2021)) contribute to TKE changes near fire fronts is still unknown. Future *in situ* monitoring efforts that incorporate high-frequency (~10 Hz) pressure measurements coupled with high-frequency sonic anemometer measurements of the three-dimensional wind field in the vicinity of fire fronts are needed to fill this knowledge gap.

In situ monitoring of the spatial variations in ambient and fire-induced turbulence patterns and processes during wildland fire events, up to this point, has focused heavily on vertical variations (e.g. vertical wind shear, buoyancy, momentum and heat fluxes) over ~2–20-m thick layers via ~10–40-m towers instrumented with sonic anemometers. Even when multiple towers have been used in wildland fire experiments that allowed for at least some assessment of the horizontal patterns of near-surface turbulent air flow that can develop in the vicinity of fire fronts, the horizontal spacing of the towers (typically 50–100 m or more) has been too large to measure horizontal variability the same way vertical variability has been measured. This shortcoming has limited our understanding of the relative importance of horizontal wind shear and horizontal turbulent fluxes of heat and momentum over distances of the order of 5–20 m (which can be substantial in the fire-front environment) in turbulence generation and heat and momentum transfer near fire fronts. Skowronski *et al.* (2021) acknowledged this shortcoming with their recently reported development of a prototypical *in situ* monitoring strategy for small (~100 m^2) experimental wildland fires. The strategy incorporated a horizontal grid of sonic anemometers spaced 2 m apart and an IR video camera to measure spatial patterns of fire-induced turbulent air flow and fire-spread variability over scales of a few metres. The strategy may provide a roadmap for future investigations of small-scale horizontal variability in turbulence regimes surrounding wildland fire fronts and its impact on fire spread.

Perhaps the most pressing and overarching question still facing the scientific community in its pursuit of understanding the connections between ABL turbulence and wildland fires is: how does ambient and fire-induced turbulent air flow in the ABL actually interact with the turbulent flame dynamics that govern the spread of wildland fires? Inherent in that question is a recognition that ABL turbulence and flame dynamics span a multitude of spatial and temporal scales, with overlap occurring primarily at spatial scales of a few metres (consistent with flame lengths) and temporal scales on the order of less than 1 min down to a few seconds or less (Finney *et al.* 2015). The laboratory studies summarised in the present review, by default, have examined fire-induced turbulence patterns and evolution at spatial and temporal scales much closer to the scales associated with flame dynamics, but they are unable to account for ABL turbulence effects. The summarised *in situ* and remote sensing studies, however, examined ABL turbulence patterns and processes at scales that were often much larger than the scales over which flame dynamics occur. The highly nonlinear nature of turbulent air flow makes the scaling up of fire-induced turbulence observations in laboratory settings to wildland fire environments and the scaling down of ambient and fire-induced ABL turbulence observations during wildland fire events to flame dynamics scales extremely difficult. Continued higher spatial and temporal resolution ABL monitoring efforts in wildland fire environments coupled with high-resolution simulations of ABL turbulence dynamics during wildland fire events are needed to more fully address the scaling problem and to develop appropriate scaling parameterisations of turbulence impacts on wildland fire behaviour. Conducting high-resolution numerical simulations of wildland fires and their impact on the atmosphere is a potential alternative and cost-effective approach to investigating turbulence dynamics, the interactions between ABL turbulence and turbulent flame dynamics, and appropriate scaling parameterisations of turbulence impacts on fire behaviour. Several modelling systems are available for this purpose, including the hydrodynamic High Gradient Flow Solver (HIGRAD; Reisner *et al.* 2000) coupled with the FIRETEC fire behaviour model (Linn *et al.* 2002), the Wildland–Urban Interface Fire Dynamics Simulator (WFDS; Mell *et al.* 2007, 2010), and the Weather Research and Forecasting Model (WRF) (Skamarock *et al.* 2008) coupled with the Clark *et al.* (2004) fire behaviour model (WRF-Fire) or the SFIRE fire-spread model (WRF-SFIRE; Mandel *et al.* 2009, 2011). However, the validation of these and other modelling systems in their predictions of fire-induced turbulence environments still depends on much-needed observational datasets focused on turbulent flow in the vicinity of fire fronts (e.g. Kochanski *et al.* 2013). Recent advances in the application of remote sensing technology (e.g. Doppler lidar and radar) for measuring turbulence regimes in wildland fire environments are also a reason for optimism in furthering our understanding of the connections between turbulence and wildland fires.

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