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FIRE SCIENCE AND MANAGEMENT (M ALEXANDER, SECTION EDITOR)

Inside the Inferno: Fundamental Processes of Wildland Fire Behaviour

Part 2: Heat Transfer and Interactions

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Abstract
Purpose of Review A wildland fire is a complex phenomenon driven by the interactions of a number of fundamental chemical and physical processes involved in the combustion and the release of heat from burning vegetative fuels. In this second article of a two-part series summarising our state of knowledge of these processes, the focus is on the physical processes involved in the transfer of the liberated heat (the generation of which is discussed in the first article) to adjacent fuel and its subsequent ignition which provides the key mechanism for sustained spread of the fire.
Recent Findings The competitive thermal degradation reactions (volatilisation versus charring) occur simultaneously at all points around a wildland fire perimeter but the extent to which one pathway dominates the other is determined by the transfer of the heat released from combusting fuel to adjacent fuel. This transfer occurs by the combination of advection, radiation and transport of burning material and may be moderated or compounded by interactions with the surrounding atmosphere or topography and by vegetation condition.
Summary The primary heat transfer processes in a wildland fire are advection (incorporating buoyancy and convection), radiation, direct flame contact and transport of burning solid material such as embers and firebrands (i.e. spotting). Other key processes involved in the transfer of heat to adjacent fuel necessary for sustained fire spread include fuel moisture, atmospheric and topographic effects, and the interactions of these with the fire. Gaps in our knowledge that limit our ability to predict the seeming capricious behaviour of wildland fires are also highlighted. The series is concluded with a discussion of how these physical processes interact with the combustion chemistry processes discussed in the first article.

Keywords Radiation · Convection · Fuel · Spotting · Firebrands · Interactions · Atmospheric · Fuel moisture

This article is part of the topical collection on *Fire Science and Management*

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Introduction

The behaviour of a wildland fire (forest fire or bushfire as it is known in some parts of the world) is the result of a large number of chemical and physical processes that occur across a range of spatial and temporal scales and which interact with each other as well as the environment around a fire [1]. In this two-part series of articles, these fundamental processes are reviewed in detail in the light of our current state of knowledge. Figure 1 is a simple conceptual model of the self-sustained propagation of a wildland fire that was used in Part 1 of this series [2] to identify key processes (identified in italics) and serve as a road map for this review series.

The first article reviewed the chemical processes involved in the combustion of cellulosic biomass fuels, and we saw that the concept of a single combustion process was insufficient to explain the broad range of behaviours observed in fires burning freely in such fuels. Instead, heating leads to two competing thermal degradation pathways as a result of the unique chemistry of cellulosic biomass fuels, volatilisation and charring. The oxidation of the products from these degradation processes results in flaming and smouldering, respectively, broadly described as combustion. These combustion reactions

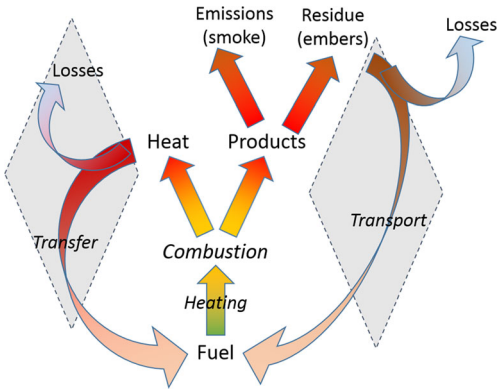

Fig. 1 A conceptual model of the self-sustained propagation of a wildland fire, which also serves as a road map for this series of review articles. Combustion generates heat and chemical products that are transferred to adjacent fuel to heat them until they ignite in a continuing reaction. The transfer and transport are not efficient and result in losses out of the system. Key processes are identified in *italics*. Breaking the cycle at any point will cause a fire to cease. This second part of the review is focused on the transfer of heat from the combustion processes and burning residue such as embers to adjacent fuels (*grey diamonds*)

release much of the energy contained within such fuels in the form of light and heat seen in the form of flames and hot gas.

The transfer of the heat and burning material generated in the combustion reactions to adjacent fuels provides the mechanisms by which a fire can become self-sustaining. If enough heat is transferred to, and absorbed by, adjacent fuel to continually initiate combustion, then the fire will actively spread and be self-sustaining [3–5]. While the physical bases of these processes are generally well understood in isolation or under strictly controlled conditions [6, 7], the interactions of these with widely varying environmental factors (e.g. the variation in distribution and spatial arrangement of vegetation, highly changeable weather and spatially variable topography), and between themselves, are less well understood.

In this article, we review the physical processes involved in the transfer of energy from the combustion zone to adjacent fuels (grey diamonds in Figure 1). Our current understanding of how environmental factors such as the weather, fuel and topography interact with these processes to influence the behaviour of wildland fires is also discussed.

Heat Transfer Mechanisms

There are three fundamental mechanisms of heat transfer—conduction, convection and radiation. The fourth that plays a significant role in free-burning fire is the transport of burning matter or solid fuel transport (also commonly known as spotting) [8, 9]. Williams [10] identified nine possible mechanisms for the transfer of heat from a free-burning fire which may be categorised by the four fundamental mechanisms:

1. Conduction
   (a) Diffusion of radicals
   (b) Heat conduction through a gas
   (c) Heat conduction through condensed materials
2. Convection
   (a) Convection through a gas
   (b) Liquid convection
3. Radiation
   (a) Radiation from flames
   (b) Radiation from burning fuel surfaces
4. Solid fuel transport
   (a) Fuel deformation
   (b) Firebrand transport.

Conduction is the transfer of internal energy via the vibrations, collisions and diffusion of molecules in an object. The effect of conduction is rather limited in most wildland fuels where fuel elements are generally highly discrete and heterogeneous, both in continuity and distribution. In very homogeneous wildland fire fuels, such as grass, fuel elements are not horizontally contiguous, and thus, conduction of heat between elements is absent. However, conduction may play a more important role in transfer of heat within larger fuel elements such as broad leaves or long stems, twigs, fallen branches and logs.

Convection is the transfer of heat through the motion of a fluid such as air (the presence of liquid-phase fuel in biomass combustion is extremely rare and short-lived [11]) and involves two primary mechanisms [12, p. 6]:

1. Conduction of heat between molecules in the fluid (or between molecules of a fluid and a solid) as a result of random molecular motion (also known as diffusion), and
2. Advection or the transfer of heat by the bulk movement of the fluid.

If the motion of the fluid is a result of the buoyancy caused by thermal expansion and the corresponding reduction in fluid density due to changes in temperature as a result of heating, then the convective transfer is described as *free* or *natural* convection [13•]. If the motion of the fluid is the result of external forces such as a fan or the motion of bodies such as a vehicle or the earth, the convective transfer is described as *forced* convection.

Radiation or radiant heat is the transmission of energy in the form of waves and includes particle or nuclear radiation, acoustic radiation such as sound waves, and electromagnetic radiation such as light. Radiant heat is electromagnetic

radiation in a very specific band of wavelengths known as the infra-red band which lies between 0.7 and 1000 μm. Unlike conduction and convection, which require the presence of a medium material in order for heat to be transferred (e.g. a fluid such as air or direct contact), electromagnetic radiation does not require a medium and can occur over a distance.

Solid fuel transport can include the transport of any burning material such as sparks, embers or firebrands out of the flaming zone into unburnt fuel. When this transport ignites a new fire, it is often referred to as spotting, as the new fire is called a spot fire. Most vegetative fuel will not undergo significant deformation but some fuel elements such as long grass stems may flex or bend sufficiently when burning to bring the burning element into contact with adjacent unburnt elements.

Thus, the primary processes driving heat transfer in a free-burning fire are the motion of gases in and around the fire (generically termed advection and incorporating convection) and radiation from the combustion zone and flames. The transport of burning material also plays a crucial role in the spread of a wildland fire [14, 15]. However, the relative importance of these processes in fire spread across the spatial and temporal scales relevant to fire propagation is yet to be well understood, despite a large number of experimental and computational studies (e.g. [16–20]) and continued investigations [21, 22•, 23].

Under very calm wind conditions, radiation has been assumed to be the dominating process for fire propagation [24–28]. Where wind is present, advection of heat air from the flame zone is the dominant mechanism [18, 29, 30••, 31]. Under laboratory wind-free conditions, radiant heat was found to account for 40% or less of the total heat flux necessary for fire spread with the remainder due to convective heat transfer [17]. Radiation from a medium-scale field experimental fire burning in grass pasture was found to represent between 15 and 19% of the total energy released during combustion [32].

However, it is not reasonable to assume that one heat transfer process happens to the exclusion of the other and thus both processes must be considered. While radiation often has a larger total heat flux than convection and acts to preheat fuels before the arrival of the flame front, fuel combustion often does not initiate until the fuel is directly contacted by the flames. This is a result of convective cooling of fine fuel particles (i.e. the exchange of heat from the heated fuel to cooler air) keeping the fuel temperature below that needed for the onset of ignition [22•, 33]. Flame contact is driven by the turbulent interaction of the buoyancy of the hot gases and particles in the flames and the advection of the air through the flame zone.

Thus, flame propagation is the cumulative result of intense short-distance radiation from both the flame and combustion zone, convective cooling of preheated fuel elements some distance ahead of the flame front, and direct contact of the fuel with turbulent flame immediately preceding the flame front.

Advection

Advection is the bulk transport of a substance or property. In our particular case, we are predominantly concerned with the advection of the air in and around a fire but also the transport of other quantities such as mass, momentum, energy, reactants and products. From these, the buoyancy generated by the combustion processes, the exchange of heat to surrounding gases, the behaviour of those heated gases that form the flames, and the effects of turbulence resulting from the interaction of contrary flows of air can be determined.

Advection of a parcel of gas such as air is the cumulative result of the forces acting upon that parcel from neighbouring parcels of air and the forces it itself exerts on those neighbours in return as well as external forces such as gravity and rotation of the Earth (i.e. Coriolis force). Figure 2 illustrates a conceptual schematic of some of the quantities important in the advection of a parcel of air. In this case, the parcel is defined on a rectangular grid (i.e. a Cartesian coordinate system) and thus provides three orthogonal directions of forces for consideration. Newton's laws of motion tells us that the rate of change of the sum of the pressure forces acting on each of the faces of the parcel acting on and within the parcel will determine the direction and magnitude of acceleration that the parcel will undergo. By applying these laws to all such parcels in the region of interest, the direction and speed of flow of the air can be determined. Similarly, exchange of other quantities such as mass, momentum and energy between parcels determines the state of the parcel including its temperature and density which combine to determine the overall behaviour of the parcel and of the flow.

Application of conservation laws and the concept of continuity (in which the molecules of a gas are considered to be *continuous* and thus to behave as a fluid rather than a collection of independent particles—i.e. the characteristic length in the domain is much longer than the mean free path of the molecules) to the motion of gases and taking velocity moments of the density distribution allows a set of governing equations that describe the motion of fluids to be constructed [34]. The resulting fluidised *equations of motion* (i.e. those derived from the principles of motion originally formulated by Newton) in the form of the Euler equations are given below.

Conservation of mass ([35, p. 74]; [36, p. 625]):

$$\frac{\partial \varrho}{\partial t} + \nabla.(\varrho \mathbf{u}) = 0, \tag{1}$$

where ϱ is density, t is time, $\mathbf{u}$ is the velocity of the parcel (with vector components u, v and w) and ∇ is the Laplacian or gradient operator (i.e. in three dimensions $\mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y} + \mathbf{k}\frac{\partial}{\partial z}$). Essentially it states that the rate of accumulation of mass in a parcel is the same as the rate at which mass flows out of the parcel.

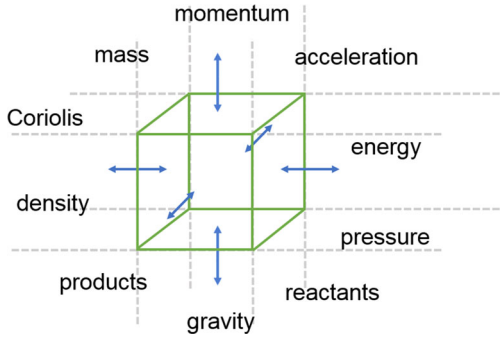

Fig. 2 A conceptual schematic of an example parcel of air based in a Cartesian coordinate systems and its physical interactions with neighbouring parcels. Some of the key quantities that can be determined from these interactions or modify the interactions are identified

Conservation of momentum ([35, p. 136]; [36, p. 625]):

$$\frac{\partial \varrho \mathbf{u}}{\partial_t} + \nabla.(\varrho \mathbf{u})\mathbf{u} + \nabla p \;\; = \;\; 0, \qquad (2)$$

where p is pressure. This equation balances the rate of increase of momentum in the parcel with the inertial, pressure and viscous forces acting on the parcel. At its most basic it is an equation for the force balance and is the application of Newton's second law ($F = ma$). It is more formally known as the Navier-Stokes equation and is used to determine the velocity of a fluid.

Conservation of energy ([36, p. 626]):

$$\varrho \frac{\partial E}{\partial t} \;\; + \;\; \nabla p - k\nabla T - \varphi = \text{constant}, \qquad (3)$$

where E is energy, k is the Boltzmann constant (coefficient of heat conduction), T is temperature of the system (K) and φ is the energy dissipation function (which takes into account irreversible production of heat through dissipation of mechanical energy). This equation essentially applies the first law of thermodynamics and describes the fact that the sum of the thermal, chemical and kinetic energy in the parcel is equal to the sum of the energy lost from, and the work done by, the parcel.

Often, an equation of state, such as the ideal gas law (i.e. $pV = nRT$) which relates a fluid's pressure in a given volume to its temperature, is used to close the system of equations.

In the specific case of a fire, chemical reactions provide additional sources and sinks of mass, momentum and energy. As a result, the right hand side of the above equations may be non-zero and non-constant, requiring additional information about the consumption of chemical reactants and generation of chemical products as well as chemical and enthalpy source closures [37••].

Solving the above equations is not a trivial task, primarily due to the non-linearity in the conservation of momentum equation in which the pressure field changes the velocity field which in turn changes the pressure field which changes the velocity field and so on. A number of simplifying assumptions or approximations are made to make the solving of the equations more tractable [38, pp. 23–40]. Some of the more commonly applied assumptions include (depending on the appropriate scale of the problem in question) the Boussinesq approximation, in which variations in fluid density are neglected; assuming the fluid is either compressible or incompressible; neglecting the Corilois force; and assuming the fluid is hydrostatic, where vertical acceleration is assumed to be much less than the magnitude of the pressure gradient force.

Convection, Buoyancy and Turbulence

The action of heat release from the chemical reactions within a combustion zone results in heated gases, both in the form of combustion products and ambient air heated by, or entrained into, the combustion products. The reduction in density caused by the heating of the gas (thermal expansion) increases the buoyancy of the gas and results in the gas rising as a plume.

The exchange of heat between two objects, such as hot air in the plume and a fuel element in the plume, is a function of the difference in temperature of the objects and always flows from the hotter object to the cooler object. It is also depends on the thermal attributes of the fluid between them and is described by convective heat transfer equation [12, p. 8]:

$$q_c = h(T_s - T_d), \qquad (4)$$

where q_c is the convective heat flux (W m^{-2}), h is the convection heat transfer coefficient of the medium (W m^{-2} K^{-1}), and T_s and T_d are the temperatures (K) of the source object and destination object, respectively. and it encompasses both diffusive and advective heat exchange. In the case where a hot object is surrounded by ambient air, T_d is the ambient air temperature and the equation describes *convective cooling*.

The exact value of the convection heat transfer coefficient depends a number of factors, including the convection mode (i.e. natural or forced) and the conditions of boundary layer around the objects [12, p. 8]. Typical values for the convection heat transfer coefficient range between 5 and 25 W m^{-2} K^{-1} for natural convection and 10 and 500 W m^{-2} K^{-1} for forced convection [13•, p. 37].

Turbulence is the non-steady or time-varying component in a flow and is often characterised as being chaotic (i.e. highly dependent upon the initial conditions). Turbulence is thought to be due to the inertia of the fluid as a whole, i.e. incorporating all sources of acceleration (time-dependent and convective), and is a key component of air flow in the open. Turbulence acts over the entire range of scales in the atmosphere, from the fine scale

of the flame to the scale of the atmospheric boundary layer. Turbulence in the form of eddies or rolls is frequently generated in the shear between two flows, such as a fast flow next to a slower flow. The interaction of the rising buoyant gas with an air flow can lead to turbulence in the flow [39•] (Fig. 3, see also 'Radiant Heat Transfer' section below).

The transition to turbulence flow from laminar flow is indicated by the non-dimensional Reynolds number, the ratio of the inertial forces to the viscous forces: [40, p. 67]

$$Re = \frac{\varrho u L}{\mu}, \quad (5)$$

where Re is the Reynolds number, u is the relative velocity between a fluid flow and surface (m s^{-1}), L is the characteristic length scale (m), and μ is the kinematic viscosity (m^2 s^{-1}). At small Reynolds numbers (e.g. <≃10), the flow is dominated by viscosity and is laminar. At high Reynolds numbers (e.g. >≃1000), the flow is dominated by the inertial forces and is turbulent. In between, the flow is transitional between the two flow regimes. The exact Reynolds number for transition from one flow regime to the other depends on attributes of the fluid and scale being considered. For the atmosphere, the Reynolds number is in the order of 60,000–90,000, which is considered highly turbulent [41].

Non-linearity produces eddy motions of smaller and smaller scales until viscous dissipation causes the cascading of energy to smaller scales to stop [42, 43]. Interaction of the flow with elements on the earth's surface, such as terrain, vegetation or structures, through the effect of drag and mechanical disturbances, can increase the rate at which energy is cascaded down the scales [44] (see 'Atmospheric Effects' section for a more comprehensive discussion).

Turbulence acts to mix heated volatile with ambient air and thus increase the rate of oxidation and flaming combustion. It also acts to mix the heated gases with unburnt fuels, heating them toward thermal degradation. Turbulence also affects the transport of burning solid fuels, such as firebrands, in the process of spotting (see 'Solid Fuel Transport (Spotting)' section). It can also act to increase the rate of glowing or smouldering combustion by improving the exchange of oxygen in the air with the reacting solid-phase char and removing insulating ash.

Where turbulence is generated by the interaction of buoyancy and advection in the flame zone of a fire, it is called convective turbulence [31] (Fig. 3). Complex fluid structures such as vortices have been observed within the flame envelope in even low-intensity flames burning in calm conditions [45, 46]. Convective turbulence immerses fuel in flame and thus leads to greater heat transfer and increased fuel ignition rates [33, 47]. This aspect of turbulent buoyant flow in and around the fuel is critical to understanding the behaviour of wildland fires, particularly in complicated fuel structures [22•]. Convective turbulence also acts to extend the range of heating from the flame zone downwind over unburnt fuels which increases with wind speed [31].

Radiant Heat Transfer

Oxidation of the gas-phase volatiles is the primary mechanism for the generation of the heat required for sustained propagation of a wildland fire, forming the flames we associate with such a fire. The gas-phase oxidation occurs via turbulent diffusion, where the hot gases from volatilisation mix diffusively with the oxygen in the

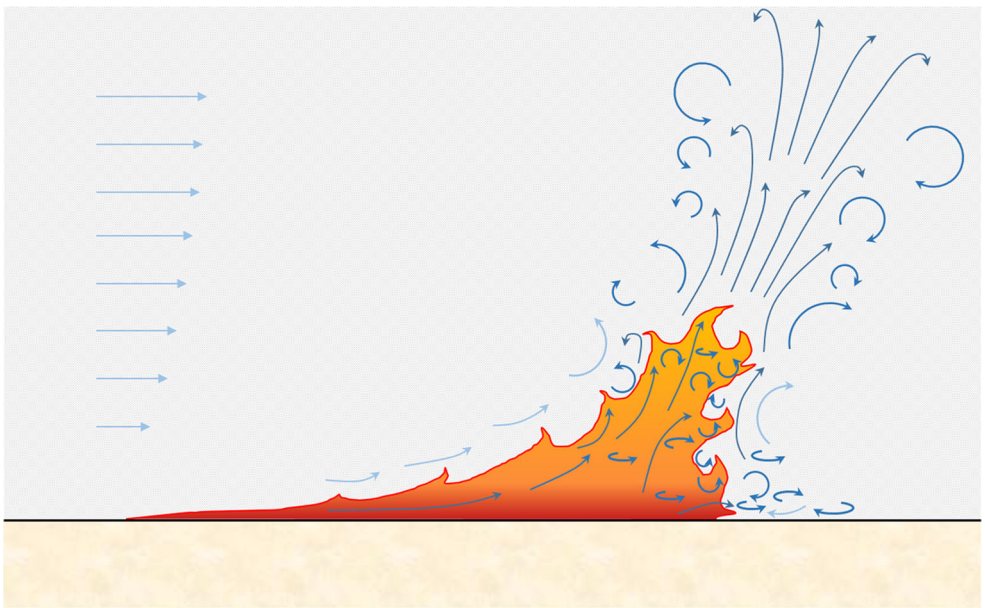

Fig. 3 A stylised two-dimensional representation of the three-dimensional turbulence generated from the interaction of the buoyancy of the flame and the ambient air flow around it. Convective turbulence acts to increase rates of mixing and combustion of volatiles and to immerse fuel ahead of the fire front in flame

cooler ambient air in a highly turbulent environment [48]. These react where conditions (e.g. mixing ratio, temperature) are suitable, in a very thin sheet at the interface between the volatiles and the air [49] called the *reaction zone* (Fig. 4). The reaction zone surrounds the envelope of volatile as it mixes and reacts with the oxygen in the air. As the fuel gas and the oxygen react only when they come in contact, the flame is also known as a non-premixed flame, to differentiate it from industrial flames where the fuel gas and air are mixed prior to being brought to ignition temperature (i.e. premixed).

It is the thermal emissions from the hot elemental carbon particles produced as a result of incomplete oxidation of the volatile species (generally in the form of soot, 10–200 nm in diameter) that we see as incandescent flame [51, 52]. However, investigations of optically thin flames from burning vegetation under laboratory conditions found that the bulk of radiant energy came from the hot gaseous products of the reaction [53]. Emissions from gaseous products such as carbon dioxide and water vapor, which are concentrated in spectral bands, form the bulk of non-luminous radiation [52, 54].

The hot carbon particles radiate electromagnetic energy as blackbodies according to Planck's energy distribution law [55, p. 199]. This distribution, based on quantum theory, relates spectral radiance to the temperature of the radiating source and the emission wavelength [12, 55]:

$$I(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{\exp\left(\frac{ch}{k\lambda T}\right) - 1}, \quad (6)$$

where I_λ is the spectral (wavelength-specific) emissive power, c is the speed of light (2.998×10^8 m s^{-1}), h is the Planck constant (6.6261×10^{-34} J s), k is the Boltzmann constant

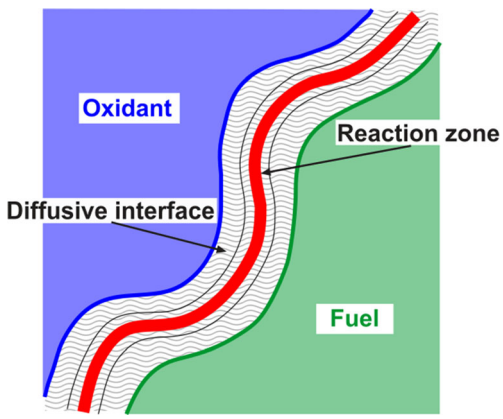

Fig. 4 A stylised representation of the diffusive interface between the gas-phase volatile fuel and oxidant (air) and the reaction zone where oxidation takes place. Temperatures in this zone can reach 1600 K. Reproduced from Cheney and Sullivan (2008) [50•], with permission from CSIRO Publishing

(1.3806×10^{-23} J K^{-1}), λ is the emission wavelength (m) and T is the emission source temperature (K). This function is shown for a small range of emission temperatures relative to wildland fire combustion in Fig. 5.

For thermal emissions, the wavelengths are in the infra-red band of the electromagnetic spectrum, ≃0.7 −1000 μm. As the kinetic energy and thus temperature of the radiating source increases, the spectral radiance increases and its peak shifts toward the visible spectrum. The nature of a flame's emission spectrum depends upon the source of the fuel and its burning conditions. A relatively low temperature will emit only a small portion of its radiation in the upper part of the visible spectrum and thus will appear a dull red. At higher temperatures, more of the radiation will appear in the visible spectrum and thus be a brighter orange or yellow. If hot enough, all the visible spectrum will be represented and will appear white.

The adiabatic (i.e. all heat is assumed to be retained in the system) temperature in the reaction zone of a range of combusting hydrocarbons is in the order of 1600 ± 100 K [13•, p. 32], which suggests that temperature of the carbon in a wildland fire flame should be similar if the carbon is in equilibrium with the gas in the reaction zone. In a typical wildland fire, the bulk of the emissions occur in the infra-red but with a good portion appearing in the yellow-orange-red bands. Band emission from electronic transitions in molecules within the reaction zone also contribute to the overall radiation from a fire, particularly that of CO_2 at around 4.3 μm [52].

As noted previously, convective turbulence is a key attribute of free-burning turbulent diffusion flames and thus the radiation emitted [56, 57]. Inside the flame zone, this turbulence acts to fold the reaction zone into a convoluted and complex shapes, resulting in overlapping of the reaction zone and the thickening of the depth of radiating particles [45, 58]. If we consider the appearance of a laminar (low-turbulence) diffusion flame (Fig. 6a, b), the reaction zone is most visible where it curves and increases its effective thickness (i.e. the reaction zone is seen end on at the edges of the flame). In a simple turbulent diffusion flame (Fig. 6c, d), the thickness of the reaction zone itself has not changed but the number of reaction zones seen at any one point has increased due to the convoluted folding and overlapping of the reaction zones, resulting in the appearance of an optically thicker, brighter flame.

In a wildland fire, the convective turbulence is high; hence flames are highly convoluted in structure and thus optically very thick. Figure 7 shows an image taken from an in-fire video of an experimental fire in mallee-heath vegetation at Ngarkat Reserve, South Australia [59]. In this image, the individual reaction zones within the flame nearest the camera are readily visible. Where reaction

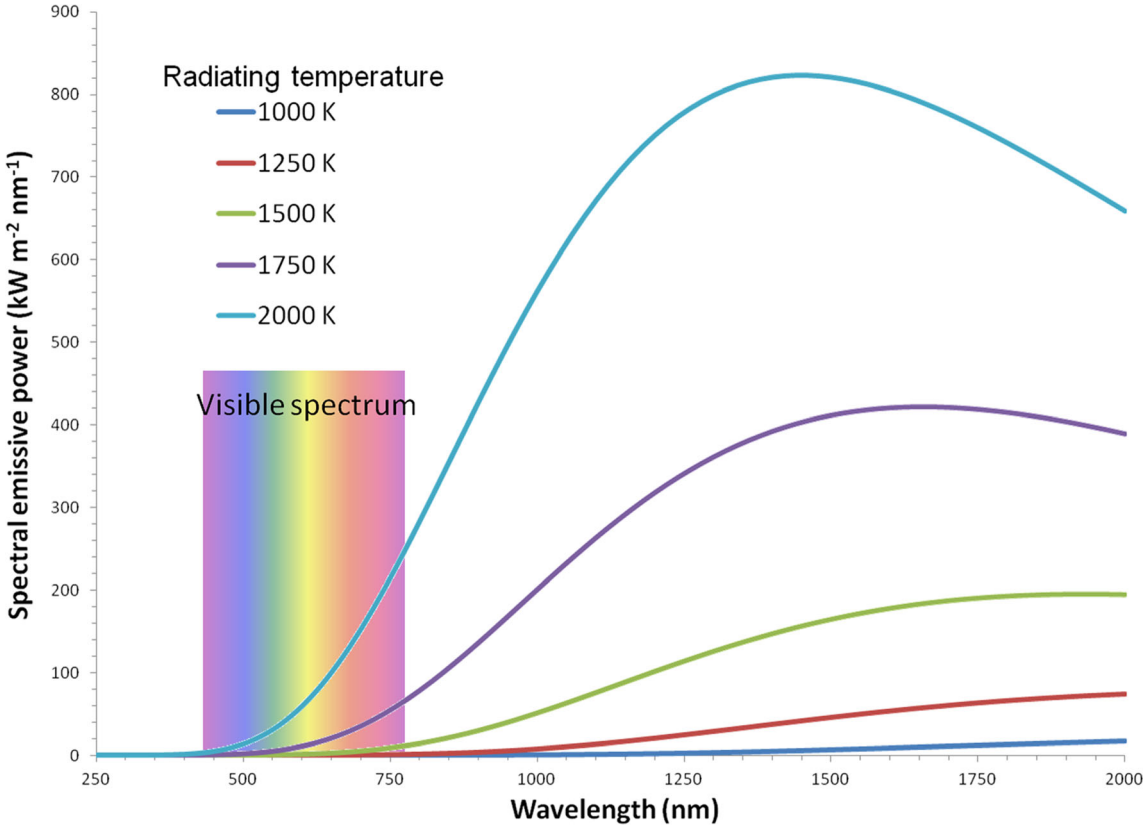

Fig. 5 Hot particles in a turbulent diffusion flame emit radiation at wavelengths according to Planck's law. The peak radiance shifts towards the visible spectrum as the temperature of the source increases. For wildland fire flames emitting at temperatures between 1500 and 2000 K, this peak is in the infra-red bands (700–1000 nm)

zones overlap, the flame is much brighter and thus radiating much more strongly, resulting in higher radiant heat flux.

The magnitude of the radiant heat emitted from a hot object is determined by the Stefan-Boltzmann radiant transfer equation. This equation, derived from the integration of the Planck

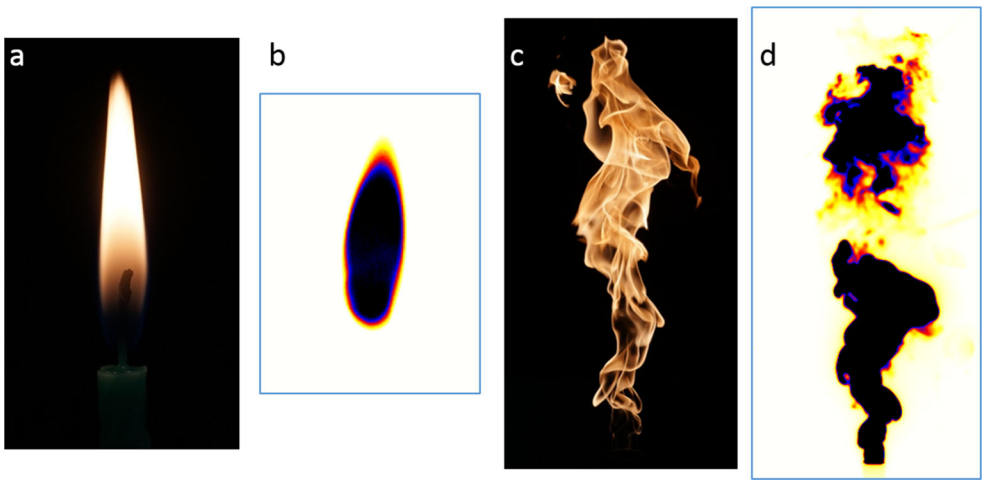

Fig. 6 **a**, **b** Photograph and infra-red image respectively of a laminar diffusion flame of a candle. Flame structure is very simple and the heat envelope (colour fringe around the black mask of the flame itself) is very thin. **c**, **d** Photograph and infra-red image of the turbulent diffusion flame emitted by a large (outlet diameter = 60 mm) Bunsen burner. A single reaction zone is present in the laminar flame and is most evident at edges where the reaction zone curves and increases in apparent thickness. A turbulent diffusion flame, however, is much more complex and exhibits multiple overlapping reaction zones apparent as bright areas where the reaction zones are thick. The heat envelope around the flame is similarly complex and extends well beyond the visible flame masked as black

Fig. 7 Image taken from an in-fire video camera at the moment the camera was immersed in the flame front. The fire was burning in mallee-heath fuels [59] and had flames in the order of 3 m tall and 1 m thick. The multiple overlapping reaction zones within the flame are clearly visible with the thickest resulting in the brightest parts of the flame

energy distribution equation (Eq. 6) across all wavelengths for all angles, is as follows:

$$q_b = \sigma T^4, \tag{7}$$

where q_b is the blackbody emissive power per unit area (W m^{-2}) of the source in all directions and at all wavelengths, σ is the Stefan-Boltzmann constant (5.67×10^{-8} J K^{-4} m^{-2} s^{-1}, which itself is a fundamental quantity related to the Planck and Boltzmann constants and the speed of light), and T is the temperature of the object (K).

Wotton et al. [60] found that the temperature profiles of flames, relative to the distance from the flame tip, from fires burning under a range of weather conditions and fireline intensities in dry eucalypt forests were consistent. The temperature of the tip of flames was between 500 and 700 K. At the base of very tall (>6 m) flames, the temperature was in the order of 1400 K, very close to the theoretical maximum adiabatic temperature. Furthermore, the findings were consistent with results from fires in other fuel types and burning conditions. Cruz et al. [58] measured similar flame structure in burning shrubs (*Erica* spp.) with peak radiant energy emissions ranging from 41 to 176 kW m^{-2} and maximum flame temperatures between 1200 and 1330 K. Measurements of peak radiant energy fluxes and flame temperature in a well-developed crown fire burning in boreal forest varied between 160 and 290 kW m^{-2} with a peak flame temperature of 1600 K [61].

In order to simplify the calculation for radiant emissions from a flame, the flame is often considered to be an emitting surface rather than a volume and a value of T chosen to represent the average temperature of that surface, typically in the range 900–1200 K [62, 63]. To account for that fact that in such a situation that the flame surface is not equivalent to a blackbody, an additional coefficient, emissivity (ε), is included in the radiant transfer equation. The emissivity of very thick (>3 m) flames may approach unity [62, 64] but it may also depend on the efficiency of combustion. Very efficient combustion in a flame will produce less carbon particles (soot) and thus have a lower emissivity.

The radiant heat flux received at a surface (such as a fuel element) from an emitting object is a function of the geometry of the receiver in relation to the emitter (size of emitting flames, distance to receiver, orientation and aspect of receiver etc.). These factors are combined into a *view factor* and applied to the radiant transfer equation with emissivity:

$$q_r = \varphi \varepsilon \sigma T^4, \tag{8}$$

where q_r is the radiant heat flux at the receiving surface (W m^{-2}), φ is the view factor incorporating the geometry relations between the receiver and emitter and ε is the emissivity of the emitting surface.

While the approximation of the flame emitting as a surface from the flame face does enable the simple application of the radiant transfer equation for an entire flame front, it does not completely capture the thermal radiation effects of the radiant emissions from a flame volume [65•] and can lead to inaccuracies in flux estimations if precise flame surface/receiver geometry (e.g. flame height and width, view factor, flame temperature and flame surface emissivity equivalents) is not known. Treating the flame front more correctly as a colloid of emitting, scattering and absorbing media over a varying volumetric shape (e.g. [66–68]) can improve the prediction of radiant heat, albeit at the expense of simplicity.

Transmission of thermal radiation from a wildland fire can be affected by a range of factors. Band absorption by certain components of the atmosphere (e.g. CO_2, H_2O) [69•, 70] can reduce total radiant heat flux. Transmission of radiant heat to surface fuels can be attenuated by interception by unburnt vegetation [65•, 71], smoke and other obstructions.

Direct Flame Contact

Evidence from field and laboratory observations in a wide range of fuels and burning conditions suggests that regardless of the amount of fuel preheating from radiated or convected heat from approaching flames, it is direct contact with the flame itself that initiates ignition and drives a fire forward [47, 72–76]. This mechanism is the result of the combination of radiation from within the flame envelope and the convective turbulence within the flame front driving flames into the unburnt fuels [22•, 77, 78].

Detailed analysis of the heating of fine (<1-mm diameter) fuels [79] showed that volatilisation and ignition of volatile oxidation was delayed by convective cooling of the fuel

despite large radiant heat fluxes; that is, ignition did not occur until the fuel was contacted directly by an impinging flame. Conversely, isolated exposure of fine dry dead fuels to hot gases at temperatures of 770 K (well in excess of the 600 K associated with the tip of the visible flame envelope from a wildland fire [58, 60, 77]) was found to result in a non-instantaneous ignition (delays of 1.3–9 s) [80]. It is thus the combination of the radiation from within the flame as well as the hot gases within the flame that enables the rapid and near instantaneous ignition of fine fuels observed in the field.

A key characteristic of direct flame contact in a fire front is its intermittent nature—the periodic flick and lick of flame that alternately engulfs and then quits fuels [81]. Finney et al. [22•] found that this intermittent flame contact in the headfire is controlled by strong instabilities in the buoyant convective flow driving the flame structure into the fuel ahead of the fire. These instabilities were found to result from the generation of streamwise vortex pairs within the flaming zone which formed peaks in the flame front where the updraughts interacted and troughs where the downdraughts interacted. The peaks and troughs were found to scale with the size of the flames.

Solid Fuel Transport (Spotting)

Spotting is the ignition of small spotfires downwind of a wildland fire by firebrands generated within the fire front [82]. This involves three sequential mechanisms—generation, transport and ignition of fuel where the firebrand lands [83–85]. In a forest fire, firebrands may consist of bark, leaves, branches or flower/seed capsules [86]. In grassfires, firebrands may consist of seed heads, clumps of grass or animal dung [50•].

Spotting contributes significantly to suppression difficulty [87], the loss of situation awareness by firefighters and others caught by the fire [88], and damage to property [89•]. Spotting enables a bushfire to overcome breaks in fuel or topography and is a key spread mechanism of fires in many forest types. It is a renowned characteristic in fires in the dry eucalypt forests of Australia [15, 89•, 90].

Due to the wide variation in firebrand sources (e.g. type, location, combustibility), potential ignition conditions (fire intensity, flame height, period of ignition etc.), combustion characteristics and the particular flight path any firebrand might take, the transport of firebrands is not amenable to a purely deterministic description. As a result, it is often described using a probabilistic or stochastic basis [83].

Two primary mechanisms lead to spotting (Fig. 8). The first is the wind-blown transport of firebrands or embers out of the flaming zone and directly ahead of the fire front and can happen practically in any wildland fire. Here, firebrands are not lofted and generally travel only a short distance (0–50 m) ahead of the fire front. In rare cases, they may be blown up to hundreds of metres if conditions are conducive.

The second is by lofting of firebrands in the convection column of the fire and their transport downwind on the prevailing wind. This can result in spotfires at distances of more than 1–2 km from the fire front [92]. Short-distance spotting (generally ≪5 km) can occur in many fuel types at any fire intensity. Long-distance spotting (≥5 km) generally requires a strong well-established convection column for lofting to sufficient height to be transported this distance [92–94]. As a result, this model of spotting predominantly only occurs in high-intensity forest fires.

The majority of firebrands generated in a bushfire will be consumed in the convection column and thus not fall out [83]. However, if the energy in the convection column is reduced (for instance, when the fire encounters a break in topography or fuel), the updraught velocity in the column is reduced, causing the firebrands to fall out of the column before they

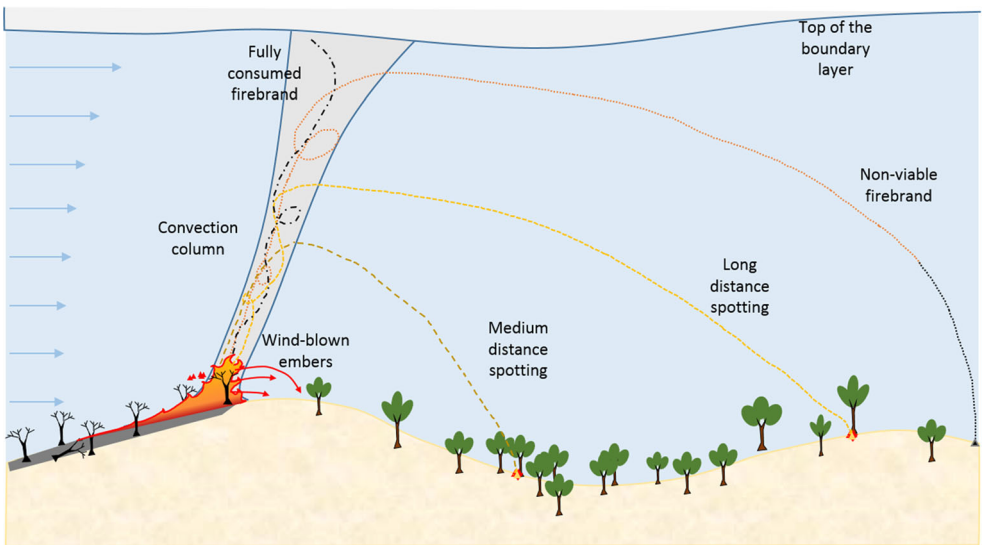

Fig. 8 Conceptual schematic of the mechanisms of spotting. Firebrands are ignited in the fire front and launched into the convection column where they are lofted. Firebrands may fall out after a short time and cause short-distance spotting. If they remain in the column longer, they may cause long-distance spotting. If they remain in the column too long, they may burn out before they hit the ground or be totally consumed. Conversely, embers may not be lofted at all but blown directly downwind of the fire front. Modified from [91]

are consumed and thus land alight, increasing the chance of a spotfire starting.

The maximum distance that a firebrand may travel is determined by the height to which it is lofted, the wind profile of the atmosphere through which it falls and the change in its terminal velocity as it burns [83, 95]. The height to which the firebrand is lofted is determined by the intensity of the fire, the updraught velocity of the convection column and the terminal velocity of the firebrand.

Whether the firebrand starts a spotfire or not when it lands is dependent upon how it was ignited and its in-flight combustion properties (such as whether it is flaming or glowing, and how long it will flame) [90, 96], and the ignition properties of the fuel on which it lands (e.g. moisture content and bulk density) [7, 89•, 97–99]. Flaming firebrands have been found to successfully initiate spotfires in litter fuels with moisture contents up to 20% oven-dry weight, independent of the wind at the fuel surface [99]. In contrast, a firebrand that is glowing can only initiate spotfires if the fuel on which it has a moisture content less than 10% and is exposed to wind of any magnitude [99].

Bark morphology is an important determinant of spotting distance. The curled bark of the ribbongum species (e.g. *Eucalyptus viminalis*) has been shown to have the potential to be carried alight for more than half an hour, sufficient time to be transported more than 35 km under severe burning conditions [15, 94].

Similarly, the transport of hot sparks or particles such as metal from clashing electricity conductors or drop-out fuses can start fires. Particle surface temperature is the critical characteristic for successful ignition from large metal particles, whereas particle surface temperature in combination with energy was critical for smaller metal particles [100]. Smaller metal particles require higher temperatures than larger particles to cause ignition.

Short- to medium-distance spotting may become the dominant fire spread mechanism for a fire burning in conducive fuel and weather conditions, particularly in very dry fuels rich in potential firebrands [86]. In such a situation, the wildland fire may no longer have a well-defined front but a series of 'pseudo' fronts comprised of groups of a large number of developing spotfires. These spotfires may interact and coalesce and may even begin to generate new spotfires. The result is a rolling series of spotfires and a very fast-moving flaming zone that can surprise unwary firefighters and residents. This occurred during the Kilmore East fire of 7 February 2009 in Victoria, Australia [101] where an area ≃25 km long by ≃3 km wide burned as a large matrix of very intense spotfires.

Other Processes and Effects

The preceding sections discussed a number of processes involved in the transfer of energy from the combustion of fuel to adjacent fuel. However, these processes rarely occur in isolation. Many of them interact across a range of spatial and temporal scales. They also interact with surrounding environment to further modify the behaviour of a wildland fire. The following section discusses some of these interactions and additional factors that can influence potential wildland fire behaviour.

Fuel Moisture Effects

The moisture content of a fuel (FMC, defined gravimetrically as the amount of water per unit mass of dry matter and expressed as a percentage) is one of the two most important environmental variables, along with wind, to influence the general behaviour of a wildland fire [16, 102]. Moisture content is the most dynamic fuel attribute, particularly of fine dead fuels, involving the interaction of thermal radiation, heat and water fluxes [103, 104••], and varies significantly with time of day, antecedent and current weather, and the fuel's physical structure [105–107]. Along with a fuel element's inherent flammability (a function of its chemical composition and morphology), moisture content critically determines a fuel element's *combustibility*, a property that describes a fuel's ability to ignite and combust [108–110], particularly the rapid changes in combustibility that can result from dramatic changes in weather conditions.

Furthermore, moisture released during combustion can reduce the transmission of radiant heat through absorption of energy in particular wavelengths [69•]. The presence of moisture can also reduce the overall temperature of flames [70]. However, the largest effect of moisture in fuels is to increase the amount of energy required to heat the fuel to initiate the thermal degradation reactions, decreasing a fuel element's combustibility and increasing the time required to ignite a fuel [99, 111]. Such effects result in slower combustion with less heat released and thus retard the spread of a fire. The overall effect depends on the type of fuel involved and the amount of moisture present. Too much moisture can result in no combustion at all. The maximum amount of moisture at which combustion is sustained is known as the moisture content of extinction. Environmental factors such as wind can increase the moisture content of extinction in some fuels through increased convective heat transfer to unburnt fuels [112]. In dead grass, this increase may be in the order of 2–3% [113, 114], and in forest litter, it could be as much as 2–30% [4]. Combustibility of dead fine fuels generally increases exponentially as FMC decreases [102] until it reaches a maximum at a FMC of 3–5%.

In fine dead fuels, any residual moisture associated with the function of plant part when it had been alive has been lost. Thus, any moisture present has come from outside the fuel, either as free liquid water from rain or dew that has soaked in from the surface or as water vapour that has diffused from the atmosphere [115]. The rate of diffusive adsorption of

atmospheric water vapour into or desorption out of the cell structure of a fuel element (consisting mostly of hydrogen bonded parallel cellulose chains forming fibrils) depends on the difference between the internal and external vapour pressures (i.e. vapour pressure deficit) and the ease of transfer [104••, 107, 116]. Given enough time, a fuel can achieve an equilibrium fuel moisture content (EMC) [117, 118] with the prevailing conditions. The length of time for this to occur has been used to characterise fuels [119–121]. Direct uptake (wicking) of water from the soil is unlikely [104••], although soil moisture may influence the fuel-level atmospheric humidity and temperature [122].

Due to its dependence on atmospheric vapour pressure, moisture in fine dead fuels will follow a diurnal adsorption/desorption trend as solar radiation, air temperature and air moisture vary through the day [115, 123]. As direct measurement of FMC is laborious, methods such as the use of a fuel simulacrum (e.g. wooden sticks of known dry mass e.g. [124–126]) or models are generally employed. The physical processes that determine fuel moisture in litter fuel involve the interaction of transfers of radiation, heat and water (e.g. [104••, 118, 127, 128]). Empirical models based on the correlation of FMC with readily measurable variables such as air temperature and relative humidity (e.g. [86, 129–132]) are often employed operationally. However, these are generally limited to a small operational range (e.g. specific fuel types, part-shade, afternoon, adsorption phase) [133], often cannot cope with free water such as rain or dew [134], and are unable to incorporate effects of rapid changes to atmospheric conditions [135, 136]. A number of techniques for estimating fuel dryness based on satellite-based or airborne remote sensing, mostly based on analysis of visual reflectance from the fuel surface, have been developed over the years (e.g. [137–140]). Recently, methods have been developed to extend these approaches to infer moisture content of fuels not directly sensed by combining remotely sensed data on atmospheric attributes such as atmospheric vapour pressure deficit measured with empirical and process-based FMC models to estimate landscape-scale fuel moisture [141, 142].

In live fuels, liquid water is transported around the plant via capillary flow through the water-conducting xylem. This moisture, initially absorbed by the roots and stored in the protoplasm and vacuoles of cells as well as within the cell walls, is emitted to the atmosphere through the leaves as water vapour via stomatal transpiration [107]. The amount of moisture depends on the plant species, the plant part, and the time of season (as the plant controls the moisture exchange with the environment and thus it does not change rapidly like fine dead fuel moisture) [143, 144]. In some live fuels, medium- to long-term drought can severely affect the moisture content [145]. Live fuel moisture content has also been found to vary due to changes in the chemical composition of live plant parts over the growing season as the plant controls moisture exchanges with the environment [146, 147].

How live fuels combust and what role live fuel moisture plays in determining fire behaviour is not clear [146, 148, 149]. Live fuels by definition have an inherent vertical component in their structure (i.e. they are generally standing) that many dead fuels (particularly litter fuels) do not; thus, combustion in some live fuels (such as tall shrubs and trees) may involve slightly different heat transfer and heat reception processes when compared to dead fuels. Live fuel moisture content was found to be a critical variable in determining the vertical development of fire spread in shrubs in the laboratory [97]; however, live fuel moisture content was not found to be an important variable in the rate of spread of crown fires in conifer forests (e.g. [150, 151]) or shrublands (e.g. [59, 152, 153]). However, in many cases, live fuels are collocated with dead fuels which can confuse the calculation of the moisture content affecting fire behaviour (e.g. [111]). In such cases, it is the combustion of the dead fuel that determines the behaviour of the fire, particularly ignitability and spread [97, 153–155], rather than the live moisture 'damping' the fire behaviour.

Atmospheric Effects

All fires exist in the planetary or atmospheric boundary layer (ABL), the layer of the atmosphere between the surface of the Earth and the bottom of the geostrophic layer. It is generally 1–2 km thick but can extend to the depth of the troposphere (10–18 km) under strong solar heating and conducive conditions, and is dominated by turbulent motions on time scales of an hour or less [156]. It is here that the exchanges of momentum, heat and water vapour with the surface that drive the weather occurs. The mean properties of the flow in this layer, known as the surface layer (i.e. the wind speed and direction, temperature and humidity), change the most in the first 50–100 m [157, p. 15].

Turbulence in the form of eddies resulting from solar heating of the surface and mechanical disturbance is a characteristic of the ABL [158, 159] (Fig. 9) and defines the wind that is the critical factor affecting the behaviour and spread of a wildland fire. The energy in the turbulence cascades from larger eddies (some of which could be the size of the depth of the ABL) to smaller eddies and eventually dissipates viscously [43]. Mixing of eddies in the ABL to the surface is felt as gusts and lulls in the wind.

The presence of a fire can perturb the air flow in the ABL [160, 161]. In addition to the heat and moisture released from the fire into atmosphere immediately around the fire [29, 162, 163], the interaction of the transport of the heated gas-phase products from combustion with the atmospheric flow also plays a significant role in the overall state of the ABL, in particular increased turbulence, and thus the behaviour of the fire [161, 164–166]. The ambient condition of the atmosphere, particularly the lapse rate (or the ease with which heated parcels of air rise within the atmosphere), determines

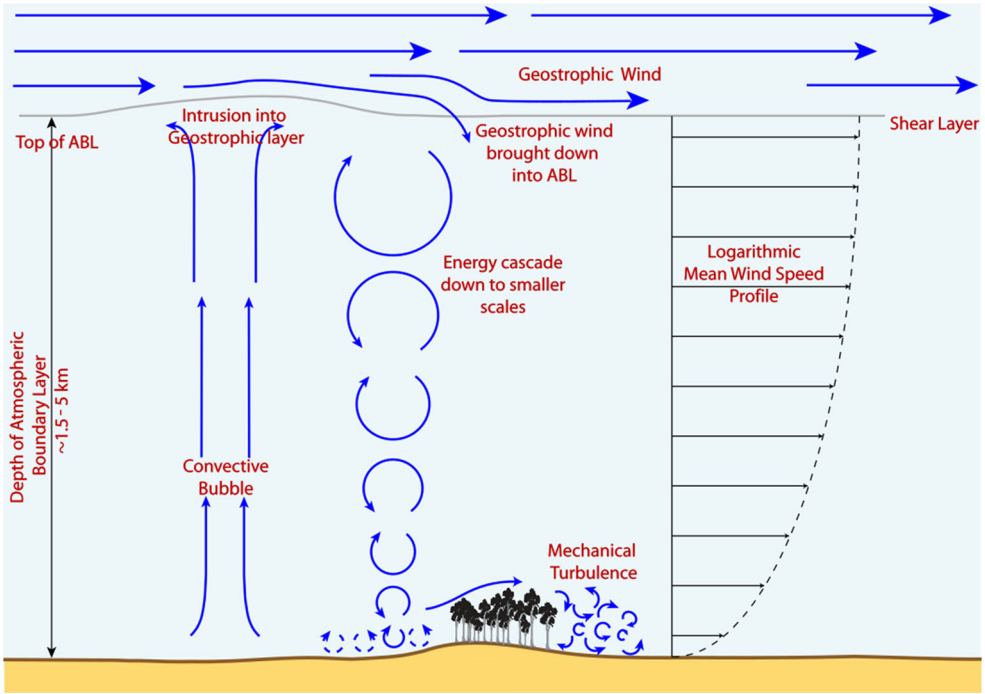

Fig. 9 A conceptual schematic of the structure of the atmospheric boundary layer, the layer of the atmosphere between the Earth's surface and the geostrophic layer where the jet stream resides. Solar heating of the Earth's surface can cause convective bubbles to form which rise to the top of the ABL and intrude into the geostrophic layer, causing jets of very fast geostrophic wind to mix into the ABL. Shear between the ABL and the geostrophic also creates turbulence. Turbulence appears as eddies in the flow which are felt on the surface as gusts and lulls in the wind. Reproduced from Cheney and Sullivan (2008) [50•], with permission from CSIRO Publishing

the impact the buoyancy of the heated air from the combustion zone will have on the atmospheric flow and any feedback mechanisms [167–169].

The buoyancy can lead to a convective plume or convection column. Large fires can generate an updraft velocity of 30–60 m s^{-1} [170, 171]. Such large-magnitude updrafts are commonly associated with strong vorticity [85, 172, 173]. The convective updraft can also be accompanied by nearby downdrafts within the ABL, with velocities about half the magnitude of the updraft [170]. Buoyancy production can interact with the ABL [174] and significantly contribute to the generation of turbulent kinetic energy in the surface layer [161, 163] as well as generate dynamic pressure gradients around the fire [163, 175]. As a result, a convergence zone can be created downwind of the plume [176] that can generate relatively strong horizontal inflow winds to the base of the plume [170, 175].

The relative strength of the buoyancy of a plume compared to that of the dynamic forces of the wind driving a fire is used to attempt to characterise whether a fire is 'wind-driven' or 'plume-dominated' and infer expectations of fire behaviour [167, 172]. The most widely used ratios are the convective Froude number [177] and Byram's energy criterion [167]. The convective Froude number is as follows:

$$F_c = \sqrt{\frac{(u-r)^2}{g\frac{\Delta\Theta}{\Theta_a}D}}, \tag{9}$$

where u is the wind speed (m s^{-1}), r is the rate of forward spread of the fire (m s^{-1}), g is gravity (9.8 m s^{-2}), $\frac{\Delta\Theta}{\Theta_a}$ is the convective buoyancy (the ratio of the difference between the ambient potential temperature, Θ_a, and the potential temperature in the convection column Θ_c) and D is the depth of the flaming zone of the fire front (m).

Byram's energy criterion or convection number, N_c, for neutrally stable, non-entraining atmosphere [167, 178, 179] is given by the following:

$$N_c = \frac{2gI}{\varrho\, c_p\, \Theta_a (u-r)^3}, \tag{10}$$

where I is Byram's fireline intensity (kW m^{-1}) [108], ϱ is air density (1.2 kg m^{-3}), c_p is the specific heat of dry air at constant pressure (1.005 J kg^{-1} K^{-1}) and Θ_a is the absolute ambient air temperature. N_c is the inverse cube of F_c when flame depth is used to define the vertical mass flux rate [180].

When the forces are relatively equal ($F_c \simeq N_c \simeq 1$), the behaviour of a fire is expected to be erratic. At F_c values much less than unity ($N_c \gg 1$), the behaviour of a fire is expected to strongly influenced by the buoyancy of the plume and at the extreme would be represented by a stationary fire such as a slash burn or log pile fire. In the converse ($F_c \gg 1, N_c \ll 1$), the fire would be expected to be strongly wind-driven. While a fire is still developing, F_c would be greater than unity but as the fire grows and its intensity increases, N_c would approach unity and then be less than it; thus, the state of a fire's development is critical. When the buoyant force far exceeds that of the inertial forces for some height above the fire (usually 300 m), blow-up characteristics (such as erratic and extreme fire behaviour) [9] are expected to occur. Byram [167] defined four ways of describing this onset:

1. The fire changes from an essentially two-dimensional to a three-dimensional phenomenon.
2. The fire changes from a forced-convection type to a free-convection type.
3. The fire acquires a convection column, instead of maintaining a smoke plume.
4. The fire 'blows up'.

The impact of neither N_c nor F_c on fire behaviour has been tested or validated against wildfire observations [177, 179]. Analysis of large fast-moving experimental grassfires found no relationship between the speed or behaviour of the fires and the critical value of unity in either N_c or F_c [180], although it is possible that the lifetime of the fires was too short for conclusive results. Jenkins [172] suggests that the critical value may be something much different to unity. The lack of conclusive evidence for either Byram's delineation of two-dimensional and two-dimensional fires or Clark's 'plume-driven' and 'wind-driven' characterisations suggests that further research is required to ascertain the utility of such classifications.

The size of a fire (simply the effective width of the headfire) affects its behaviour [181–183], with wider fires spreading faster than narrower fires burning in the same conditions. A fire starting from a point will steadily increase its width as a result of lateral spread and changes in wind direction and simultaneously increase its rate of forward spread. It will continue doing so until it reaches a given width for the prevailing conditions at which point it will no longer increase in speed (i.e. it has reached the quasi-steady rate of spread for the prevailing conditions) [113]. Analysis of simulations of a physical model [184] suggest that it is the competition between the buoyancy of the flanks of the fire and the buoyancy of the headfire that drives this process—a wider fire will result in more of the prevailing wind reaching the headfire and thus driving it forward than a narrower fire where the flanks divert more of the wind from the headfire. Such a suggestion has yet to be verified by experimental data, either from the laboratory or field.

Changes in the ambient meteorological conditions, such as wind speed and direction, moisture, temperature and lapse rate, both at the surface and higher in the ABL, can have a significant impact on the state of the fuel (moisture content), the behaviour of a fire and its development and growth. Synoptic scale structures in the atmospheric flow, such as dry middle-tropospheric air [185] and upper-level jet systems [186], can have dramatic effects on the behaviour of a fire. Other atmospheric structures such as fire whirls [187–190] or pyro-cumulus cloud [191, 192] can be generated in the presence of a fire given suitable environmental conditions [193, 194]. The presence of such structures might themselves in turn affect the spread and behaviour of the fire but the mechanisms for many of these are not clear.

Topographic Effects

The topography in which a fire is burning also plays a critical role in the way in which energy is transferred to unburnt fuel and the ambient atmosphere. The ground is an impervious boundary that defines the bottom of the ABL and is a source of friction to the flow over it [195]. Vegetation further increases the amount of friction through the roughness length as well as being the layer of the atmosphere through which the fire moves [196].

Fires spread faster up a slope than they do on flat ground [197, 198]. Operational rules of thumb suggest this increase can range from a few percent to a doubling for every ten degrees of slope [86, 199, 200]. The physical mechanisms that are involved in this are not well understood [201] but may include interactions between the atmosphere and the topography such as the acceleration on windward slopes of air in the surface layer [202, 203], increased propagating heat flux (radiative or convective) as a result of decreased angles between fuel and buoyant flames [204, 205], increased potential for direct flame contact or immersion with fuels (particularly in shallow surface fuels), attachment of flames to the slope by the Coanda effect [206, 207] or combinations thereof.

Investigation of laboratory fires burning in pine needles in the absence of wind [21] found that radiative heating dominated heat transfer on slopes up to 20°. However, close to the fire (<10 cm) and on slopes greater than 20°, the heat transfer was dominated by convection. Clements and Seta [163] found that convective heat generated from a fire on a positive slope was transported in the lowest 2 m of the surface layer which also contained the highest plume temperature, suggesting that fire spread on slopes in the open is driven primarily by the advection of very hot gas in the fuel layer [46, 207]. Convective cooling of fires on slopes may act to restrict the lateral growth of fires [208] and keep them narrow. The effect of slope in taller fuels with lower bulk density (e.g. heath and tall grasses) may be much reduced [209] as heat transfer processes (i.e. convection (including direct flame immersion of unburnt fuel) and radiation) within the fuel bed may dominate flame propagation [47, 210]. The effect of slope on the propagation of sections of the perimeter other than the head has not been quantified and is critical knowledge for high fidelity prediction of fire perimeter propagation over landscapes.

Changes in fire behaviour on slopes may be further confounded by changes in fuel type or condition with elevation [211] or changes in moisture content due to changes in solar radiation with elevation, aspect and slope [105, 132].

The interaction of the topography with the atmosphere also results in changes to the air flow over the land surface which can influence the behaviour and spread of a fire. The surface, particularly complex geometry surfaces as found in hilly, broken or mountainous terrain, induces turbulence in the air flow over it by causing flow separation and the formation of eddies

[212] which can lead to wind directions at odds with the bulk (synoptic) motion of the air. Orographic channeling (e.g. gully or valley winds) can also result in wind strengths and directions that are greatly different to the prevailing winds [213, 214].

Differential solar heating of the surface can lead to the generation of small-scale vortices (called whirlwinds or willy-willies) and also differential in fuel moisture contents. Diurnal heating and cooling of the ground can result in generation of upslope (anabatic) or downslope (katabatic) winds. Lee slope rotors (eddies that form in lee of hills where the flow over the crest separates from the surface of the hill) can result in flow up the lee slope opposite to the prevailing wind [215]. Alternatively, streamwise flow down the lee slope may act to overcome the negative impact of the downslope on fire spread. There is currently no coherent theory to predict which flow regime (flow separation or streamwise flow) will occur for a given situation [156, p. 170]. Factors that influence the flow regime may include atmospheric stability (i.e. lapse rate), wind conditions, surface roughness and the morphology (aspect ratio) of the hill itself [202]. Lee slope turbulence can also induce the formation of vortices that may affect fire behaviour [204, p. 96] [216].

In many fuel types, such as Australian dry eucalypt forest, the retarding effect of negative slopes on fire spread may not occur at all due to the fire spotting over the downslope section and initiating spread on the next up slope [88, 89•]. Thus, fire spread on downslopes may not play any significant part in the propagation of a well-developed fire across a landscape that is topographically complex as spotfires may carry the fire from ridgetop to the next windward slope [86]. However, the new spotfires will have to undergo initiation and development phases each time, and this may have a retarding effect on the overall rate of forward spread of the fire [217]. This development time may be reduced in situations where high-density spotting (as can occur under extreme fire weather conditions [101]) dominates fire propagation. For high-intensity fires burning under strong winds and which are spotting and crowning, slope may only be important for the first 30 or so minutes [86, 129].

Discussion

Free-burning fires spreading under consistent wind on flat topography in uniform fuels form an elongated shape closely resembling an ellipse or egg shape [8, 218]. This observation has been used to generate geometric approximations for fire perimeter propagation (e.g. [219–221]). The aspect ratio of the ellipse has been related to the wind speed [222, 223], with stronger winds producing thinner, longer ellipses. Slight changes in wind direction act to broaden the fire perpendicular to the mean wind direction [224], resulting in an increase in the rate of spread of the fire. More significant changes in wind direction causes the flanks of the fire to become, in turns, heading or backing fires, depending on the direction of the wind, which cause those parts of the perimeter to increase or decrease its rate of spread accordingly.

Figure 10 shows the final spread interval of an experimental fire conducted in grasslands of the Northern Territory, Australia [181]. The fire was ignited in *Themeda australis* grass from a 47-m-long line, and in this image, it has been burning for 118 s in an average wind of 5.5 m s^{-1} blowing from the bottom left of the image to the top right. The headfire is clearly delineated by very deep and tall flames leaning in the direction of spread with the wind and a narrowing of the headfire into a parabolic shape. The depth and height of the flames reduces along both flanks towards the back of the fire where the flames are very low, in some places indiscernible. There is very little outward spread of the flanks or into the wind at the rear of the fire in comparison with the length of the ignition line. Considerable smoke is generated from smouldering combustion behind the flame front but very little smoke is visible from the flames.

Due to the relatively small size of the fire (≃50 × 100 m), at any point in time, the combustion conditions (fuel, moisture, ambient air temperature, relative humidity and wind speed) around the perimeter are essentially the same. The only notable differences are the direction of the wind with respect to the spread of the fire and the mode of combustion. In the section of fire perimeter spreading against the wind (i.e. backing fire), the fuel is consumed from the base of the fuel bed up; in the section of fire spreading with the wind (i.e. heading flames), fuel is consumed from top of the fuel bed down [50•]. Clearly, there are factors other than the way the fuel is consumed that contribute to the amount of flame produced at the head of the fire compared to the back—orders of magnitude more flame by volume in some instances.

Fig. 10 Aerial photograph of an experimental fire 118 s after ignition. The fire was lit in *Themeda australis* grass from a 47-m-long ignition line. Average wind speed was 5.5 m s^{-1}; average rate of spread was 1.95 m s^{-1}. The difference in structure between the flames at the head of the fire and those at the back is clearly shown. The wind is blowing from the bottom left corner of the photograph to the top right, as suggested by the direction of the passage of smoke. From [225]

While differences in the rate of combustion and net heat flux around the perimeter obviously play a part in determining the observed differences in fire behaviour, these are driven primarily by differences in the rate of volatilisation. The only environmental difference between the head of a fire and the back of the fire is the relation of the direction of the wind to the perimeter. Given the importance convective cooling of fuels has on combustion, this orientation of the flame zone with respect to the wind may result in a significant difference in the temperature of the fuel substrate in the combustion zone with the fuel at the rear of the fire cooler than that at the head.

The current understanding of wildland fire dynamics does not suggest a reason that this should affect the behaviour of the combustion zone. However, the sensitive dependence of the combustion chemistry on temperature (through the exponential Arrhenius reaction rate) as described in part 1 of this series [2] is critical to determining which combustion path will dominate. The exothermic but lower activation energy pathway of charring may dominate when ambient temperature (i.e. <300–315 K) wind is applied and acts to cool the thermally degrading fuel in the combustion zone (generally >600 K). If such convective cooling is not present, either because the wind has been heated to much greater than ambient temperature or the wind is shielded from the fuel, then the higher activation but endothermic pathway of volatilisation may dominate, leading to a greater portion of flaming combustion.

Once volatilisation and flaming combustion begins to dominate, more heat is transferred to adjacent fuel, resulting in a positive feedback that increases the rate of volatilisation and thus subsequently more flame and more heat to be transferred. The direction of transfer of the bulk of the convective heat from the flames is biased by the direction of the air flow in and around the flaming zone which is driven by the mean direction of the wind. As a result, the net heat flux is greater at the head than that at the rear or flank.

The relatively low net heat flux at the rear, however, does not mean that the fire goes out at this location [226]. Char formation and oxidation results in a considerable reservoir of heat retained in the fuel bed at the rear and on the flanks that will rapidly transition to a headfire if there is a change in wind direction. This behaviour can potentially put firefighters at risk as this section of fire perimeter can spread unexpectedly fast [227].

The low activation energy and exothermic formation of char and the higher activation energy but endothermic formation of volatiles and the strong dependence of these reactions upon temperature also provides an explanation for the observed stop-start behaviour of wildland fires (i.e. the seemingly capricious nature of wildland fires [228]). Efforts to correlate the short-term spread of the fire with the gust structure of the wind (e.g. [81, 229]) have found no relation between the two, suggesting that the stop-start spread of a wildland fire is not primarily the result of the gust structure in the wind, although the wind certainly plays a critical role in the behaviour of the flames. The understanding of the competitive thermal degradation of biomass fuel suggests that the interaction between the exothermic and endothermic reactions at the head of a wildland fire will result in a see-sawing of the energy release as the exothermicity drives the reactions toward volatilisation and as the rapid release of volatiles drives the system toward char formation and so on, resulting in alternating bursts of rapid forward spread and little or no forward spread, giving the appearance of stop-start behaviour.

Conclusions

This two-part article has provided only the briefest of glimpses into some of the fundamental chemical and physical processes involved in the behaviour of a wildland fire. While part 1 [2] focussed on the chemistry of combustion and the release of energy from fuel in the form of heat and light, this concluding article has focussed on the mechanisms involved in the transfer of that heat to adjacent fuel, closing the cycle required for sustained spread. It also discussed other processes essential to understanding the behaviour of wildland fires.

The thermal degradation of cellulosic biomass results in the competitive formation of either volatiles or char. It occurs simultaneously at all points around a fire perimeter but the extent to which one formation process dominates the other is determined by the total heat flux received by adjacent fuel. This heat flux is transferred by the combination of advection, radiation and transport of burning material. The heating of adjacent fuel may be moderated by convective cooling via interactions with the ambient temperature wind. At the rear of the fire, where the reaction zone is open to the ambient wind, char is formed preferentially over volatiles. At the head of the fire, where the reaction zone is essentially blocked from the effect of ambient wind, volatile formation dominates. The flanks of the fire alternate between heading and backing behaviours, depending on the fine-scale shifts in wind direction. Both char and volatiles combust in air through oxidation but result in different behaviours—volatile combustion produces flames with rapid heat release, while char combustion produces glowing combustion with a slow but greater heat release. As a result of both the change in preferential formation of thermal degradation species around the fire perimeter and the difference in their combustion morphology, there is a distinct difference in the observed spread and behaviour around a fire perimeter.

Advection, the transport of air and other quantities, is the primary mechanism for the transfer of heat from the combustion zone to adjacent fuels. It encompasses convective heat transfer and other fluid motions such as turbulence. The interaction of the ambient wind with the convection of the fire results in convective turbulence that is responsible for direct

contact of flame with fuel, driving the propagation of the fire front. Radiation from the flames and combustion zone contributes significantly to heat transfer to adjacent fuels, particularly in direct flame contact. Convective cooling, the advection of heat away from fuels that are being heated, generally delays the onset of ignition of fine fuels until immersion in flame. The transport of burning material in the convection column provides the key mechanism that allows fires to overcome breaks in fuel and topography that would otherwise retard the spread of a fire. It is particularly prevalent in forest fuels where there is an abundance of potential firebrand material such as bark which often enables a fire to jump over downslope topography and discontinuities in the fuel.

Other key factors that affect the way in which fuels are heated include the moisture in the fuel, which can decrease the combustibility of a fuel. Moisture released from combustion can also inhibit the transfer of radiant heat from the flames to adjacent fuel. Atmospheric effects, particularly turbulence cascading down through the atmospheric boundary layer but also generated from interaction with vegetation, structures and fire itself, play a dominant role in determining the bulk weather attributes that influence the state of the fuels and the wind driving the fire. Interactions with the fire can result in small- and large-scale atmospheric structures such as whirls and pyrocumulonimbus cloud that can further modify the environment in which a fire is burning. Topography similarly can alter the environment. In particular, topography can modify the direction and speed of surface winds affecting a fire, through channelling of the flow and modification of vegetation but also as a result of turbulence generated in the lee of ridges. It can also enhance the advected and radiated heat reaching fuels, increasing the rate of combustion and thus speed of the fire.

Returning to our conceptual model of the factors and processes involved in determining the behaviour of a wildland fire (see [2], Fig. 9), we can see from the current article that the transfer of heat from the combustion processes can happen via a number of mechanisms, each of which can interact separately with key environmental factors such as the topography and the atmosphere. Figure 11 is an extension of the conceptual model to include these new mechanisms and interactions.

The underlying chemical processes identified in the previous conceptual model remain. The additional heat transfer mechanisms identified here: advection, radiation and mass transfer interact with environmental factors such as the topography and the atmosphere to alter the efficiency with which the energy generated in combustion is transferred to adjacent fuels. Sometimes, the efficiency is decreased as losses of energy to the atmosphere increase; sometimes, the efficiency is increased, and the fire spreads faster.

There remain many gaps in our understanding of wildland fire behaviour; some we know about; and many, presumably, we do not [14]. For the most part, our study of fire behaviour has focussed on the behaviour of the headfire, the most active section of fire perimeter which causes most concern for fire suppression and personal safety. In relative terms, however, we know very little about the behaviour of the other sections of the perimeter, namely the flanks and rear of the fire. In

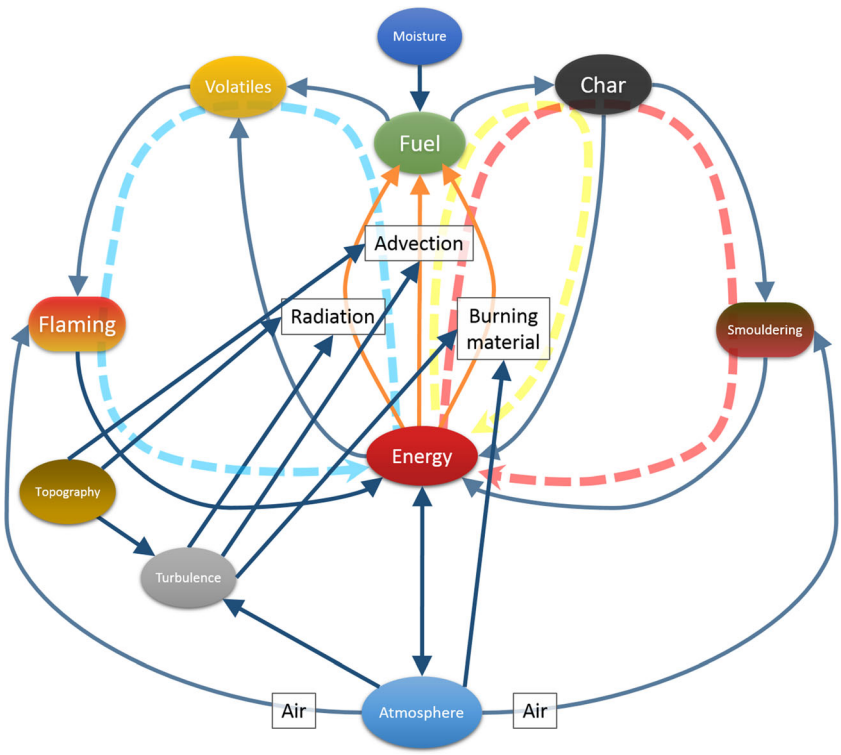

Fig. 11 An extension to the conceptual model presented in [2] that captures the heat transfer mechanisms and their interactions with key environmental factors such as fuel moisture, topography and the atmosphere. The underlying chemical processes remain the same; however, some components have been broadened such as heat and air. *Arrows* indicate direction of flows. The interaction of the topography and the atmosphere is a source of turbulence that can affect all three heat transfer mechanisms. Topography by itself can affect the advection and radiant heat transfer to fuel. These additional processes and factors do not alter the underlying chemical and thermal feedbacks defined previously

particular, we know very little about the interactions of these sections with other processes and environmental factors such as topography, the wind field and turbulence. Such information is essential to being able to predict with confidence the movement of an entire fire perimeter across the landscape, a key requirement to being able to determine the effect of changes in wind direction.

We know that initiating fires starting from a point take time to build up in speed and intensity and achieve what is described as 'steady-state' behaviour. However, we have very little insight into the period of time or length of distance it takes for a fire to build up (e.g. [204, 230, 231]). Often, the speed of a fire builds up before the fire achieves its full flame dimensions. Understanding not just the processes involved in the development of a fire but also the dynamics that can evolve in the interactions of the processes as a fire increases in size, intensity and speed is also crucial.

In many avenues of endeavour associated with wildland fires (e.g. fire safety, preparation of fire breaks, fire suppression, and design and construction of safer houses), it is ancillary components of fire behaviour that are important. For example, being able to predict the length of flames is critical to knowing if a fire will breach a gap in a fire break; the height of flames is a key characteristic used by firefighters to determine suppressability of a fire [232]. These ancillary components may be related to fire spread but often are influenced by their own self-contained set of processes and factors that influence their outcome.

Similarly, understanding the processes and interactions involved in fires burning under environmental conditions different to that associated with a wildfire is lacking. Such conditions are critical to the safe execution of prescribed burning for hazard reduction. Furthermore, understanding conditions conducive to fire spread sustainability under marginal burning conditions is also required. Conversely, identification of when a fire will escape containment is currently not available.

In most cases, the key lack of knowledge is the precise state of the environment in which a fire is burning, particularly of that of the fuel: its type, condition and availability in terms of combustibility. Even with good knowledge of the processes and their interactions involved in the behaviour of a wildland fire, it is quite often this lack of precise knowledge of fuels at the landscape scale that diminishes our ability to predict wildland fire behaviour.

Further research is required to better identify and quantify the key processes and their interactions involved in the behaviour of wildland fire in all the fuel, weather and topographic conditions in which they occur. Doing so will enable improved prediction of the likely behaviour of wildland fires under any conditions and will help to further reduce the social, economic and environmental impact of wildland fires around the world.

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Compliance with Ethical Standards

Conflict of Interest Dr. Sullivan declares no conflicts of interest.

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