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Review

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International Journal of Wildland Fire **2009**, *18*, 349–368

Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models

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Abstract. In recent years, advances in computational power have led to an increase in attempts to model the behaviour of wildland fires and to simulate their spread across the landscape. The present series of articles endeavours to comprehensively survey and précis all types of surface fire spread models developed during the period 1990–2007, providing a useful starting point for those readers interested in recent modelling activities. The current paper surveys models of a physical or quasi-physical nature. These models are based on the fundamental chemistry and physics, or physics alone, of combustion and fire spread. Other papers in the series review models of an empirical or quasi-empirical nature, and mathematical analogues and simulation models. Many models are extensions or refinements of models developed before 1990. Where this is the case, these models are also discussed but in much less detail.

Introduction

History

The field of wildland fire behaviour modelling has been active since the 1920s. The work of Hawley (1926) and Gisborne (1927, 1929) pioneered the notion that understanding of the phenomenon of wildland fire and the prediction of the danger posed by a fire could be gained through measurement and observation and theoretical considerations of the factors that might influence such fires. Despite the fact that the field has suffered from a lack of readily achievable goals and consistent funding (Williams 1982), the pioneering work by those most affected by wildland fire – the foresters and other land managers – has led to a broad framework of understanding of wildland fire behaviour that has enabled the construction of operational models of fire behaviour and spread that, although not perfect for every situation, at least allow a practical prediction of likely behaviour.

In the late 1930s and early 1940s, Curry and Fons (1938, 1940) and Fons (1946) brought a rigorous physical approach to the measurement and modelling of the behaviour of wildland fires. In the early 1950s, formal research initiatives by Federal and State Government forestry agencies around the world commenced concerted efforts to build fire danger rating systems that embodied a fire behaviour prediction component in order to better prepare for fire events. In the US, this was through the Federal US Forest Service and through State agencies; in Canada, this was the Canadian Forest Service; in Australia, this was through the Commonwealth Forestry and Timber Bureau in conjunction with various State authorities.

In the 1950s and 1960s, spurred on by incentives from defence budgets, considerable effort was expended exploring the effects of mass bombing (such as occurred in Dresden or Hamburg, Germany, during World War Two) and the collateral incendiary effects of nuclear weapons (Lawson 1954; Rogers and Miller 1963). This research effort was closely related to large forest or conflagration fires and had the effect of bringing additional research capacity into the field (Chandler *et al*. 1963). This resulted in a boom in the research of wildland fire behaviour. The 1970s saw a dwindling of research interest from defence organisations. By the 1980s, research into the behaviour of wildland fires returned to those that had direct interest in the understanding and control of such phenomena, i.e. the land and fire management agencies, and was of occasional interest to journeyman mathematicians and physicists on their way to bigger, and more achievable, goals.

An increase in the capabilities of remote sensing, geographical information systems and computing power during the 1990s resulted in a revival in the interest of fire behaviour modelling, this time applied to the prediction of fire spread across the landscape.

Background

The present series of papers endeavours to comprehensively survey and précis the extensive range of modelling work that has been conducted in wildland fire during the period 1990–2007 and to act as a starting point for those interested in recent modelling activities. The range of methods that have been undertaken over the years represents a continuous spectrum of possible modelling (Karplus 1977), ranging from the purely physical (those that are based on fundamental understanding of the physics and chemistry involved in the combustion of biomass fuel and behaviour of a wildland fire) through to the purely empirical (those that have been based on phenomenological description or statistical regression of observed fire behaviour). In between is a continuum of approaches from one end of the spectrum or the other. Weber (1991*a*) in his comprehensive review of physical wildland fire modelling proposed a system by which models were described as physical, empirical or statistical, depending on whether they accounted for different modes of heat transfer, made no distinction between different heat transfer modes, or involved no physics at all. Pastor *et al*. (2003) proposed

10.1071/WF06143 1049-8001/09/040349

descriptions of theoretical, empirical and semi-empirical, again depending on whether the model was based on purely physical understanding, of a statistical nature with no physical understanding, or a combination of both. Grishin (1997) divided models into two classes, deterministic or stochastic-statistical. However, these schemes are rather limited given the combination of possible approaches. Given that describing a model as semi-empirical or semi-physical provides no indication as to which half is empirical or physical, a more comprehensive and complete convention is necessary.

Thus, the present series is divided into three broad categories: physical and quasi-physical models; empirical and quasi-empirical models; and simulation and mathematical analogue models. In this context, a physical model is one that attempts to represent both the physics and chemistry of fire spread; a quasi-physical model attempts to represent only the physics; an empirical model contains no physical understanding at all (generally only statistical in nature); and a quasi-empirical model is one that uses some form of physical framework on which the statistical modelling is based. Empirical and quasi-empirical models may be further categorised into laboratory-based and field-based to differentiate fully controlled small-scale experiments conducted indoors and those that have limited control in the open. Simulation models are those that implement a pre-existing fire behaviour model (often of low spatial dimensionality) in a landscape spread application and thus address a different set of computation-related problems. Mathematical analogue models are those that utilise a mathematical precept rather than a physical one for the modelling of the spread of wildland fire.

Since 1990, there has been rapid development in the field of spatial data analysis, e.g. geographic information systems and remote sensing. Following this, and the fact that there has not been a comprehensive review of fire behaviour modelling since Weber (1991*a*), I have limited the present review to works published since 1990. However, as much of the work that will be discussed derives or continues from work carried out before 1990, such work will be included in much less detail in order to provide context.

Previous reviews

Many of the reviews that have been published in recent years have been for audiences other than wildland fire researchers. Recent reviews (e.g. Perry 1998; Pastor *et al*. 2003), while endeavouring to be comprehensive, have offered only superficial and cursory inspections of a limited range of models. Morvan *et al*. (2004) analysed a much broader spectrum of models and concluded that no single approach is going to be suitable for all uses. Mell *et al*. (2007) provided a brief overview of physical models and proposed a scheme in which models were defined by the component on which the model was focussed: fuel, atmosphere or fire.

Although the recent reviews provide an overview of the models and approaches that have been undertaken around the world, mention must be made of significant reviews published much earlier that discussed the processes in wildland fire propagation themselves. Foremost is the work of Williams (1982), which comprehensively covered the phenomenology of both wildland and urban fire, and the physics and chemistry of combustion, and is recommended reading for the beginner. The earlier work of Emmons (1963, 1966) and Lee (1972) provides a sound background on the advances made during the post-war boom era. Pitts (1991) reviewed the considerable work done on the effect of wind on fire behaviour since World War Two. Grishin (1997) presented an extensive review of the work conducted in Russia in the 1970s and 1980s.

This particular article will discuss those models based on the fundamental principles of the chemistry and physics, or physics alone, of wildland fire behaviour (physical and quasi-physical models). Later articles in the series will discuss those models based on observation of fire behaviour (empirical and quasi-empirical models) and on mathematical analogies to fire spread (simulation and mathematical analogues).

Physical and quasi-physical modelling of wildland fire

Much of the fundamentals of wildland fire behaviour covering the chemistry and physics of combustion and heat transfer are given in texts such as Blackshear (1974); Incropera and DeWitt (1985); Williams (1985); Drysdale (1985); and Pyne *et al*. (1996). A brief discussion of the elements of physical and quasi-physical modelling is followed by a discussion of the models that have appeared in the literature 1990–2007. Where possible, the chronological development of each model is followed based on the order of appearance of articles in the literature. As the laws of physics are the same no matter the origin of the modeller or the location of development of the model, physical models are essentially based on the same processes and it is only the choice of the governing equations describing those processes and their implementation and solution that differs in each model.

Wildland fire is the complicated combination of energy released (in the form of heat) owing to chemical reactions (primarily involving the oxidation of thermal decomposition products of vegetation) in the process of combustion and the transport of that energy to surrounding unburnt fuel and the subsequent ignition of that fuel. The former is the domain of chemistry and occurs on the scale of molecules, and the latter is the domain of physics and occurs on scales ranging from millimetres up to kilometres (Table 1). It is the interaction of these processes over the wide range of temporal and spatial scales involved in wildland fire that makes the modelling of wildland fire behaviour such a difficult task.

Grishin (1997, p. 81) proposed five relatively independent stages in the development of a deterministic physical model of wildland fire behaviour:

1. Physical analysis of the phenomenon of wildland fire spread; isolation of the mechanism governing the transfer of energy from the fire front into the environment; definition of the medium type, and creation of a physical model of the phenomenon.
2. Determination of the reaction and thermophysical properties of the medium, the transfer coefficients and structural parameters of the medium, and deduction of the basic system of equations with corresponding additional (boundary and initial) conditions.
3. Selection of a method of numerical solution of the problem, and derivation of differential equations approximating the basic system of equations.

Table 1. The major biological, physical and chemical components and processes occurring in a wildland fire and the temporal and spatial (vertical and horizontal) scales over which they occur

Type	Time scale (s)	Vertical scale (m)	Horizontal scale (m)
Combustion reactions	10^{-20}–10^{2}	10^{-4}–10^{-2}	10^{-4}–10^{-2}
Fuel particles	–	10^{-3}–10^{-2}	10^{-3}–10^{-2}
Fuel complex	–	1–20	1–10^{2}
Flames	10^{-2}–30	0.1–10	0.1–2
Radiation	10^{-9}–10	0.1–10	0.1–50
Conduction	10^{-2}–10	10^{-2}–10	10^{-2}–10
Convection	1–10^{2}	0.1–10^{2}	0.1–10
Turbulence	0.1–10^{-3}	1–10^{3}	1–10^{3}
Spotting	1–10^{3}	0–3 × 10^{3}	1–10^{5}
Plume	1–10^{5}	1–10^{5}	1–10^{2}

Table 2. Physical models published in the literature 1990–2007
Planes of movement are: *x*, direction of spread or mean wind; *y*, horizontally perpendicular to direction of spread; and *z*, vertical

Model	Author (Year)	Origin	Dimensions	Plane
Weber	Weber (1991)	Australia	2	*xy*
AIOLOS-F	Croba *et al*. (1994)	Greece	3	–
FIRETEC	Linn (1997)	USA	3	–
Forbes	Forbes (1997)	Australia	1	*x*
Grishin	Grishin *et al*. (1997)	Russia	2	*xz*
IUSTI	Larini *et al*. (1998)	France	2	*xz*
PIF97	Dupuy *et al*. (1999)	France	2	*xz*
FIRESTAR	Morvan *et al*. (2001)	France	2	*xz*
LEMTA	Séro-Guillaume *et al*. (2002)	France	2(3)	*xy*
UoS	Asensio *et al*. (2002)	Spain	2	*xy*
UoC-R	Zhou *et al*. (2005)	USA	3	–
WFDS	Mell *et al*. (2007)	USA	3	–

4. Programming; test check of the program; evaluation of the accuracy of the difference scheme; numerical solution of the system of equations.
5. Testing to see how well the derived results comply with the real system; their physical interpretation; development of new technical suggestions for ways of fighting wildland fire.

Clearly, stages one and two represent considerable hurdles. Indeed, identification and formulation of the processes involved in the behaviour of wildland fire is problematic; fundamental research into the best methods to represent the phenomenon of wildland fire processes is still very active and sometimes cause for contention (Di Blasi 1998). In many cases, determination of the reaction and thermophysical properties depends on the form of the formulation chosen for a particular process. Similarly, the choice of method to solve the appropriately formed governing equations and validation of the results are not simple matters and are whole fields of endeavour unto themselves.

The most distinguishing feature of a fully physical model of fire spread in comparison with one that is described as being quasi-physical is the presence of some form of combustion chemistry. Although both are based on conservation principles (in particular conservation of energy), it is this component, often derived from the fundamental chemistry of the fuel and its combustion, that determines the rate and amount of energy released from the fuel, and thus the amount of energy to be subsequently transferred to surrounding unburnt fuel and the atmosphere, etc. Quasi-physical models, however, contain no chemistry but rely on a higher-level (often empirical) model to determine the magnitude of energy to be transferred. This energy model generally requires information about the flame geometry to be known *a priori* (or at least to be iteratively determined based on some equation of state) to close the system of equations and may not necessarily be internally self-consistent.

Physical models

This section describes each of the physical models that appeared in the literature 1990–2007 (Table 2). Many are based on the same basic principles and differ only in the methodology of implementation or the purpose of use. They are presented in chronological order of first publication. Some have continued development, some have been implemented and tested against observations; others have not. Many are implemented in only one or two dimensions in order to improve analytical or computational feasibility.

Where information is available, an indication of the intended use and feasibility of real-time simulations for operational use is given. Although it is recognised that some models were never intended for operational use for fire perimeter spread prediction,

the capability is certainly of great interest to many practitioners and so is used as a metric for comparison and discussion of the models.

Weber (Australian Defence Force Academy, Australia)

Weber's (1991*b*) model was an attempt to provide the framework necessary to build a physical model of fire spread through wildland fuel, rather than an attempt to actually build one. To that end, Weber highlights several possible approaches but does not give any definitive answer. Weber begins with a reaction-transport formulation of the conservation of energy equation, which states that the rate of change of enthalpy per unit time is equal to the sum of the spatial variation of the flux of energy and heat generation. He then formulates several components that contribute to the overall flux of energy, including radiation from flames, radiation transfer to fuel through the fuel, advection and diffusion of turbulent eddies. Heat is generated through a chemical reaction that is modelled by an Arrhenius law that includes heat of combustion.

The initial result is a model that is one-dimensional in x plus time. Advection, radiation and reaction components allow the evolution of the fluid velocity to be followed. Solid-phase and gas-phase fuel are treated separately owing to different energy absorption characteristics.

In a more realistic version of this model, Weber treats the different phases more explicitly, producing two coupled equations for the conservation of energy, one for each phase. The coupling comes from the fact that when the solid fuel volatilises, it releases flammable gas that then combusts, returning a portion of the released energy back to the solid for further volatilisation.

Weber determines that in two dimensions, the solution for the simple model is a two-dimensional travelling wave that produces two parametric equations for spatial x and y and that yields an ellipse whose centre has been shifted. Weber favourably compares this result with that of Anderson *et al*. (1982), who first formalised the spread of a wildland fire perimeter as that of an expanding ellipse. This model is not intended for operational use and is only of academic interest.

AIOLOS-F (CINAR SA, Greece)

AIOLOS-F was developed by CINAR SA, Greece, as a decision-support tool for wildland fire behaviour prediction. It is a computational fluid dynamics model that utilises the three-dimensional form of the conservation laws (i.e. conservation of mass, momentum and energy) to couple the combustion of a fuel layer with the atmosphere to model forest fire spread (Croba *et al*. 1994). It consists of two components, AIOLOS-T, which predicts the local wind field and wind–fire interaction, and AIOLOS-F, which models the fuel combustion.

Gas-phase conservation of mass is used to calculate the local wind perturbation potential, the gas-phase conservation of momentum is used to determine the vertical component of viscous flow, and a state equation is used to predict the air density and pressure change with air temperature (Lymberopoulos *et al*. 1998).

The combustion model is a three-dimensional model of the evolution of enthalpy from which the change in solid-phase temperature is determined. A radiation heat transfer equation provides the radiant heat source term. Fuel combustion is modelled through a 3-D fuel mixture-fraction evolution that is tied to a single Arrhenius law for the consumption of solid-phase fuel. The quantity of fuel consumed by the fire within a time interval is an exponential function of the mixture-fraction.

The equations are solved iteratively and in precise order such that the wind field is solved first, then the enthalpy, mixture-fraction, and temperature second. These are then used to determine the change in air density, which is then fed back into the wind field equations taking into account the change in buoyancy due to the fire. The enthalpy, mixture-fraction and temperature are then updated with the new wind field. This is repeated until a solution converges, then the amount of fuel consumed for that time step is determined and the process continues for the next time step.

Fuel is assumed to be a single layer beneath the lowest atmosphere grid. Fuel is specified from satellite imagery on grids with a resolution in the order of 80 m. No data on calculation time are given, although it is described (Croba *et al*. 1994; Lymberopoulos *et al*. 1998) as being faster than real time and so may have operational utility.

FIRETEC (Los Alamos National Laboratory, USA)

FIRETEC (Linn 1997), developed at the Los Alamos National Laboratory, USA, is a coupled multiphase transport–wildland fire model based on the principles of conservation of mass, momentum and energy. It is fully three-dimensional and employs a fully compressible gas transport formulation to represent the coupled interactions of the combustion, heat transfer and fluid mechanics involved in wildland fire (Linn *et al*. 2002*b*). A hydrodynamics model called HIGRAD (Reisner *et al*. 1998, 2000*b*, 2000*a*) is used to solve equations of high gradient flow, such as the motions of the local atmosphere, outside the bounds of FIRETEC.

FIRETEC is described by the author as self-determining, relying solely on the formulations of the physics and chemistry to model the fire behaviour. The model utilises the finite volume method and the notion of a resolved volume to solve numerically its system of equations. It attempts to represent the average behaviour of the gases and solid fuels in the presence of a wildland fire. Many small-scale processes such as convective heat transfer between solids and gases are represented without each process actually being resolved in detail (Linn 1997; Linn and Harlow 1998*b*; Linn *et al*. 2002*a*). Fine-scale wind patterns around structures smaller than the resolved scale of the model, including individual flames, are not represented explicitly.

The complex combustion reactions of a wildland fire are represented in FIRETEC using a few simplified models, including models for pyrolysis, char burning, hydrocarbon combustion and soot combustion in the presence of oxygen (Linn 1997). Linn *et al*. (2002*a*) refined this to a much simplified chemistry model that reduced the combustion to a single solid–gas phase reaction.

It is assumed that the rates of exothermic reaction in areas of active burning are limited by the rate at which reactants can be brought together in their correct proportions (i.e. mixing-limited). Colman and Linn (2007) further refined the combustion model to separate the formation of volatiles via pyrolysis of solid fuel and the combustion of volatiles. Colman and Linn (2003)

proposed a procedure to improve the combustion chemistry used in FIRETEC by utilising a non-local chemistry model in which the formation of char and tar are competing processes but no results have yet been published.

The conservation of mass in the system is tied to the creation and consumption of solid and gas-phase fuel; coefficient of drag for the solid fuel is included in the conservation of momentum equation and a turbulent diffusion coefficient, derived from a turbulent Reynolds stress tensor, is included in the conservation of energy equation. Later formulations (Linn *et al*. 2005; Linn and Cunningham 2005; Cunningham and Linn 2007) used more precisely defined fuel structures to more accurately model effects of drag due to vegetation.

A unique aspect of the FIRETEC model is that the variables that occur in the relevant solid- and gas-phase conservation equations are divided into mean and fluctuating components and ensemble averages of the equations taken. This approach is similar to that used for the modelling of turbulence in flows such as the Reynolds-averaged Navier–Stokes equations. The concept of a critical temperature within the resolved volume is used to initiate combustion and a probability distribution function of temperature based on the mean and fluctuating components of quantities in the resolved volume used to determine the mean temperature of the volume. Once the mean temperature exceeds the critical temperature, combustion commences and the evolution equations are used to track the solid- and gas-phase species. The critical temperature is chosen to be 500 K (Linn 1997).

Turbulence in the flow around the combusting fuel is taken into account as the sum of three separate turbulence spectra corresponding to three cascading spatial scales, viz.: the scale of the largest fuel structure (i.e. a tree), 4.0 m; the scale of the distance between fuel elements (i.e. branches), 2.0 m; and the scale of the smallest fuel element (i.e. leaves, needles, etc.), 0.05 m (Linn 1997). By representing turbulence explicitly, the effect of diffusivity in the transfer of heat can be included.

The original version of FIRETEC did not explicitly include the effects of radiation, from either flame or fuel bed, or the absorption of radiation into unburnt fuel – primarily because flames and flame effects were at an unresolved scale within the model. As a result, fires failed to propagate in zero-wind situations or down slopes. Later efforts (Colman and Linn 2003, 2005, 2007) have incorporated non-local combustion of pyrolysis gases in order to more properly model radiation from flames.

Because FIRETEC models the conservation of mass, momentum and energy for both the gas and solid phases, it does have the potential, via the probability density function of temperature within a resolved volume, to track the probability fraction of mass in a debris-laden plume above the critical temperature (Linn and Harlow 1998*a*) and thus provide a method of determining the occurrence of 'spotting' downwind of the main fire.

Running on a reasonably large supercomputer with 64 processors, a FIRETEC simulation using $160 \times 160 \times 41$ cells at a uniform horizontal grid resolution of 2 m (vertically non-uniform from 1.5 to 30 m) took 1–2 min for every second of simulation time (Colman and Linn 2007). Thus, a 200-s simulation would take in the order of 3.3–6.7 h. And so, although this model is not suitable for operational fire spread prediction, its comprehensive treatment of physical processes makes it very suitable for research purposes, including study of fire dynamics, fuel treatment effects and fire planning.

Forbes (University of Tasmania, Australia)

Forbes (1997) developed a two-dimensional model of fire spread utilising radiative heat transfer, species consumption and flammable gas production to explain why most forest fires don't become major problems and why, when they do, they behave erratically. The main concept behind the model is a two-path combustion model in which the solid fuel of eucalypt trees either thermally degrades directly and rapidly in an endothermic reaction, creating flammable fuel gas that then combusts exothermically, or produces flammable 'eucalypt vapours' endothermically that then combust exothermically.

Forbes developed a set of differential equations to describe this process and, because the reaction rates are temperature-dependent, a temperature evolution for both the solid and gas phases. This is the sum of radiation and conduction (only included in the solid phase) heat fluxes, convective heat loss, and the endothermic reaction losses in the production of the two competing flammable gases. Wind is included in the reaction equations.

Forbes concludes from his analysis of the one-dimensional form of the equations that a travelling wave solution is only sustainable if one of the two reaction schemes is endothermic overall and, as this would not be the case in a large, intense bushfire, that bushfires are unlikely to propagate as simple travelling waves. He determined a solution of a one-dimensional line fire but found that for most parameter values, the fire does not sustain itself. He found that the activation energies for each reaction, rate constants and heat release coefficients govern the propagation of the fire. Low activation energies and temperatures and high heat release rates are most likely to lead to growth of large fires.

Forbes then develops a two-dimensional solution for his equations, making the assumption that the height of the processes involved in the vertical direction (i.e. the flames) is small (i.e. by some orders of magnitude) when compared with the area of the fire. This solution produces an elliptical fire shape stretched in the direction of the wind. He suggests improving the model by including fuel moisture. No performance data are given.

Grishin (Tomsk State University, Russia)

The work of A. M. Grishin has long been recognised for its comprehensive and innovative approach to the problem of developing physical models of forest fire behaviour (Weber 1991*b*). Although most of this work was conducted and published in Russia in the late 1970s and early 1980s, Grishin published a major monograph in 1992 that collected the considerable research he had conducted in one place, albeit in Russian. This monograph was translated into English (Grishin 1997) and for the first time all of Grishin's work was available for English readers, and this is the main reason for the inclusion of his work in the current review.

Grishin's model, as described in several papers (e.g. Grishin *et al*. 1983, 1984; Grishin 1984; Grishin and Shipulina 2002), was based on analysis of experimental data and developed using the concepts and methods of reactive media mechanics. In this formulation, the wildland fuel (primarily forest canopy)

and combustion products represent a non-deformable porous-dispersed medium (Grishin 1997). Turbulent heat and mass transfer in the forest, as well as heat and mass exchange between the near-ground layer of the atmosphere and the forest canopy are incorporated. The forest is considered as a multiphase, multi-storeyed, spatially heterogeneous medium outside the fire zone. Inside the fire zone, the forest is considered to be a porous-dispersed, six-phase, two-temperature, single-velocity, reactive medium. The six phases within the combustion zone are: dry organic matter, water in liquid state, solid products of fuel pyrolysis (char), ash, gas (composed of air, flying pyrolytic products and water vapour), and particles in the dispersed phase.

The model takes into account the basic physicochemical processes (heating, drying, pyrolysis of combustible forest material) and utilises the conservation of mass, momentum and energy equations in both the solid and gas phases. Other equations, in conjunction with initial and boundary conditions, are used to determine the concentrations of gas-phase components, radiation flux, convective heat transfer, and mass loss rates through Arrhenius rate laws using experimentally determined activation energies and reaction rates. Grishin uses an effective reaction whose mass rate is close to that of CO to describe the combustion of 'flying' pyrolytic materials, because he determined that CO is the most common pyrolytic product (Grishin *et al*. 1983). Numerical analysis then enables the structure of the fire front and its development from initiation to be predicted.

Although the model is formulated for three spatial dimensions (x, y and z) plus time, the system of equations is generally reduced to a simpler form in which the vertical dimension (z) is averaged over the height of the forest and the fire is assumed to be infinite in the y direction, resulting in a one-dimensional plus time system of equations in which x is the direction of spread. The original formulation was intended only for the acceleration phase from ignition until steady-state spread is achieved (Grishin *et al*. 1983). This was extended using a moving frame of reference and a steady-state rate of spread (ROS) to produce an analytical solution for the ROS that was found to vary linearly with wind speed (Grishin 1984).

The speed of the fire front is taken to be the speed of the 700 K isotherm. The domain used for numerical analysis is in the order of 100–200 m long. Rate of spread is found to be dependent on initial moisture content of the fuel. Owing to the analytical form and low spatial dimensionality of the model, it is only of academic interest but may possibly form the basis of more operationally-oriented models.

IUSTI (Institut Universitaire des Systèmes Thermiqes Industriels, France)

IUSTI (Larini *et al*. 1998; Porterie *et al*. 1998*a*, 1998*b*, 2000) is based on macroscopic conservation equations obtained from local instantaneous forms (Larini *et al*. 1998) using an averaging method first introduced by Anderson and Jackson (1967). It aims to extend the modelling approach of Grishin *et al*. (1983) to thermal non-equilibrium flows. IUSTI considers wildland fire to be a multiphase reactive and radiative flow through a heterogeneous combustible medium, utilising coupling through exchange terms of mass, momentum and energy between a single gas phase and any number of classes of solid phases. The physicochemical processes of fuel drying and pyrolysis due to thermal decomposition are modelled explicitly. Whereas FIRETEC was intended to be used to model wildland fire spread across large spatial scales, the initial form of IUSTI concentrated on resolving the chemical and conservation equations at a much smaller spatial scale at the expense of three-dimensional solutions. Later work (Porterie *et al*. 2007) extends the model to three dimensions and considers larger scales.

A set of equations describing the general analysis of the reactive, radiative and multiphase medium was derived (Larini *et al*. 1998; Porterie *et al*. 1998*a*), then reduced to a much simplified version (called a zeroth order model) in which the effects of phenomena were dissociated from those of transfers. This was done by undertaking a series of simplifying assumptions. The first assumption was that solid particles are fixed in space, implying that solid-phase momentum is null; there is no surface regression and no char contribution in the conservation equations, and the only combustion process is that of pyrolysis in the gaseous phase. Mass loss rates are deduced from Arrhenius-type laws following on from the values used by Grishin *et al*. (1983) and Grishin (1997) and thermogravitic analysis (Porterie *et al*. 2000). Mass rate equations for the conversion of solid fuel (gaseous production and solid fuel mass reduction) assume an independent reaction path between char formation and pyrolysis such that the rate of particle mass reduction relative to thermal decomposition of the solid phase and gas production rate is the sum of all the solid fuel mass loss rates due to water vaporisation, pyrolysis, char combustion (as a consequence of pyrolysis), and ash formation (as a consequence of char oxidation from the idealised reaction, $C + O_2 \rightarrow CO_2$). The pyrolysis products are assumed to be removed out of the solid instantaneously on release. Mass diffusion of any chemical species is neglected and no chemical reactions occur in the solid phase. A single one-step reaction model in which fuel reacts with oxidant to produce product is implemented.

A later version of IUSTI (Porterie *et al*. 2000) utilises the density-weighted or Favre average form of the conservation equations due to the density variations caused by the heat release. The time-averaged, density-weighted (Favre) fluctuation of turbulent flux is approximated from Boussinesq's eddy viscosity concept and the turbulent kinetic energy, κ, and dissipation rate, ε, are obtained from the renormalisation group theory.

The formation of soot is modelled as the soot volume fraction that forms mostly as a result of the pyrolysis process and so is assumed to be a percentage of the mass loss rate due to pyrolysis. The radiative transfer equation is based on the mole fraction of the combustion products and the average soot volume fraction, treating the gas as grey.

Drag is included through the drag coefficient, which is a function of the Reynolds number of the solid phase. Solid-phase particles are treated as spheres. The conductive and convective heat transfer coefficient is expressed using the Reynolds number for flow around cylinders.

The governing equations of conservation in both gas and solid phases are discretised on a non-uniform grid using a finite-volume scheme. The domain over which the equations of the early form of the model are solved was in the order of 1–2 m long by 0.1 m with an average resolution of $\sim$0.01 m. Porterie *et al*. (2007) implemented the model in 3-D at a larger

scale sufficient to simulate small field experiments in which the domain was $50 \times 60 \times 20$ m high with a non-uniform grid of $140 \times 14 \times 35$ cells and a time step of 0.025 s. They found, to the limits of the experimental data, that their model simulated the spread and shape of the experimental fires well.

IUSTI took 57 h to simulate 150 s of fire spread on a desktop computer (Intel Pentium-D 3.2 GHz). Although not suitable for operational fire spread prediction, IUSTI has potential for operational planning tasks and for research purposes.

PIF97 (Institut National de la Recherche Agronomique, France)

The detailed work of Larini *et al*. (1998), Porterie *et al*. (1998*a*) and Porterie *et al*. (2000) provided the framework for the development of a related model, PIF97 (Dupuy and Larini 1999; Morvan and Larini 2001). The aim of this work was to simplify the multiphase IUSTI model of Larini *et al*. (1998) and Porterie *et al*. (1998*a*) in order to develop a more operationally feasible model of wildland fire spread. The full 2-D IUSTI was reduced to a quasi-two-dimensional version in which the fuel bed is considered to be one-dimensional and the gas interactions (including radiation and convective mixing above the bed) are two-dimensional (x and z). In a manner similar to IUSTI, two phases of media are considered – gas and solid. However, PIF97 assumes that the solid is homogeneous, unlike IUSTI, which considers multiple classes of the solid phase.

PIF97 has two main components: the first is a combustion zone model that considers the radiative and convective heat transferred to the fuel bed in front of the flaming zone. The radiative component considers radiation flux from adjacent fuels, the ignition interface, flame and the ambient media surrounding the fuel. Radiation from solids is assumed to be blackbody at a temperature of 1123 K. This value was selected so that the model could predict the spread of a single experimental fire in pinaster needles. Convective heat exchange depends on the Nusselt number, which is approximated through a relation with the Reynolds number for the type of flow the authors envisage. This in turn relies on the assumption of flow around a cylinder of infinite length. Mass transfer and drag forces are similarly derived using approximations to published models and empirical correlations (i.e. assuming cylindrical particles). An ignition temperature for solid fuel of 600 K is used. The second component is the fire-induced flow in the flaming combustion zone behind the ignition interface. This depends on the ROS of the interface derived from the combustion part of the model. The temperature of this gas is assumed to be fixed at 900 K.

The numerical solution of PIF97 is based on a domain that is 25 cm long and uses a spatial resolution of 1 mm. Results of the model are compared with experimental results presented by Dupuy (2000) in which two radiation-only models, that of de Mestre *et al*. (1989) and a one-dimensional version of Albini's (1985, 1986), were compared with laboratory experiments conducted with *Pinus pinaster* and *P. halepensis* needles. PIF97 was found to be comparable with the Albini model, except in *P. halepensis* needles, where it performed better.

FIRESTAR (Université de la Mediterranée–INRA, France)

IUSTI also provided the framework for the development of a related model, FIRESTAR. Initially, a one-dimensional version of the multiphase model of Larini *et al*. (1998) and Porterie *et al*. (1998*a*) was constructed in an attempt to simplify IUSTI (Morvan and Dupuy 2001). A numerical experiment replicating fire spread through a tube containing pine needles (in order to replicate one-dimensional spread experimentally) was conducted. Results showed a linear increase in ROS with increasing wind speed up to a value of 16 cm s^{-1}. Beyond this value, ROS dropped off dramatically and pyrolysis flow rate reduced. Analysis of the species composition mass fractions showed that below 16 cm s^{-1}, the combustion was oxygen-limited and was akin to smouldering combustion. Above 16 cm s^{-1}, the combustion became fuel-limited as the increased air flow increased convective cooling and slowed pyrolysis and hence ROS.

Morvan and Dupuy (2004) extended FIRESTAR to 2-D and multiple classes of solid-phase fuel in order to simulate Mediterranean fuel complexes comprising live and dead components of shrub and grass species, including twigs and foliage. An empirical correlation was used for the drag coefficient based on regular shapes (i.e. cylinder, sphere, etc.) A renormalised group κ–ε turbulence model using turbulent diffusion coefficients was incorporated and a pressure correction algorithm used to couple the pressure with the velocity. This model was implemented as a 2-D vertical slice (x and z) through the fire front as a compromise between the computational time and need to study the main physical mechanisms of the fire propagation. A series of 80×45 control volumes, each 10×3 cm were used, defining a domain 8 by 1.35 m. ROS was defined as the movement of the 500 K isotherm inside the pyrolysis front. ROS was compared with other models and observations of shrub fires (Fernandes 2001) and did not perform well.

Dupuy and Morvan (2005) added a crown layer to this model, resulting in six families of solid-phase fuel: three for shrubs (leaves and two size classes of twigs (0–2, 2–6 mm), one for grass, and two for the overstorey *Pinus halepensis* canopy (needles and twigs 2–6 mm). This version implemented a combustion model based on Arrhenius-type laws after Grishin (1997). Soot production (for the radiation transfer) was assumed at 5% of the rate of solid fuel pyrolysis. The domain was 200×50 m high with, at its finest scale, cells 0.25×0.025 m, average of 0.25×0.25 m and largest 1.0×0.25 m. A simulation of 200 s took 48 h on an Intel Pentium P4 2 GHz machine.

FIRESTAR remains a 2-D model but is presently being converted to 3-D (Morvan *et al*. 2006). The highly detailed representation of the vegetation and the subsequent effect on flows provide advantages over the similar IUSTI but are still not capable of modelling faster than real time for operational purposes.

LEMTA (Laboratoire d'Énergétique et de Mécanique Théorique et Appliquée, France)

This comprehensive model (Séro-Guillaume and Margerit 2002) considers a two-phase model, gas and solid, in three regions of a forest – above the forest, in the forest and below the ground – at three scales: microscopic (plant cell solid–gas level), mesoscopic (branch and leaf level) and macroscopic (forest canopy–atmosphere level). They identify but do not investigate a fourth scale, that of the 'gigascopic' or landscape level.

The combustion chemistry is simplified in that only gas-phase combustion is allowed. Solid-phase chemistry only considers

pyrolysis to gas-phase volatile fuel, char and tar. Soot production is not considered, nor is char combustion. Gas phases include O_2, water, N_2, fuel and inert residue. Solid-to-gas-phase transitions are handled by interface jump relations.

Conservation of species mass, momentum and energy are derived for mesoscopic gas- and solid-phase interactions. These are then averaged over the larger macroscopic scale by using distribution theory and convoluting the equations to macroscopic quantities. Extended irreversible thermodynamics is then used to close the system of equations. Arguments about thermal equilibrium are used to further reduce the non-equilibrium equations for temperature and pressure.

The system of equations is then further simplified using assumptions about the nature of the fuel (at rest) and the size and interaction of the fuel particles with the gas phase (i.e. no advection, pressure or porosity variations in the solid phase). Drag is not included. Gas-phase equations in the region above the forest do not include solid-phase particles and, as soot is not modelled, cannot suitably describe radiant heat from flames.

Margerit and Séro-Guillaume (2002) and Chetehouna *et al*. (2004) reduced Séro-Guillaume and Margerit (2002) to two dimensions in order to produce a more operationally feasible fire spread model. Margerit and Séro-Guillaume (2002) achieved this through assumptions that the scale of the fuel to the fire was such that the fuel could be considered a boundary layer and the fire a one-dimensional interface between burning and unburnt fuel on the surface (i.e. the fuel is thin relative to the width of the fire). A few assumptions are then made: there is no vertical component in the wind, the solid and gas phases are in thermal equilibrium, and the non-local external radiative heat flux is blackbody. The resulting two-dimensional model is a reaction-diffusion model similar in form to Weber (1991*b*). Assumptions about the speed of chemical reactions are made to get the pyrolysis occurring at an ignition temperature.

Chetehouna *et al*. (2004) further reduced the two-dimensional reaction-diffusion equations of Margerit and Séro-Guillaume (2002) by making simplifying assumptions about the evaporation and ignition of the solid-phase fuel. Five distinct heating stages are used, each separated by the temperature of the fuel: (1) fuel heating to 373 K; (2) moisture evaporation at 373 K; (3) fuel heating to ignition temperature; (4) combustion at 573 K; and (5) mass loss due to chemical reactions and heat loss at flame extinction.

Separate equations with different boundary conditions are used for each stage but only stages 1–3 are important for fire spread. The equations for these stages are then non-dimensionalised and a limiting parameter, the thermal conductivity in the solid phase, is used as a parameter for variation. The equations are then solved as an eigenvalue problem as a series expansion in the thermal conductivity in order to determine the ROS for each stage. Two flame radiation models are used to incorporate long-distance radiant heat flux from flames: de Mestre *et al*. (1989) and the version given by Margerit and Séro-Guillaume (2002). Predicted ROS are similar for both flame models, with LEMTA predicting rates slightly less than de Mestre *et al*.

The model is then simulated on a computer. It provides a circular shape in no wind and no slope, and an elongated shape under wind. An example burning in real terrain is shown but no discussion of its performance against real fires is given. Mention is made of the reduced version of LEMTA operating in real time on a PC and this may provide the potential for an operational model.

UoS (University of Salamanca, Spain)

Asensio and Ferragut (2002) constructed a 2-D model of fire spread that used radiation as the primary mode of heat transfer but also incorporated advection of hot gas and convective cooling of fuels. The model, described here as UoS, employed a simplified combustion chemistry model (two phases: gas and solid, and two species: fuel and oxygen) and utilised only conservation of energy and species mass. It is assumed combustion is fuel-limited and thus only one species is conserved. Arrhenius laws for fuel consumption are used. Turbulence is not accounted for directly or explicitly, but a term for advection with a wind velocity vector is included.

The model is of a form that explicitly includes convective heating, radiation, chemical energy release and natural (free) convection. Non-dimensionalised forms of the system of equations are then discretised into a finite element form for numerical computation. The model is considered to be a first step and the authors aim to link it to the Navier–Stokes equations for better incorporation of turbulence.

Asensio *et al*. (2005) attempted to provide a link from the 2-D surface fire spread of UoS to a model of convection above the fire. The model starts with the conservation of momentum equation and then makes hydrostatic assumptions about the atmosphere. It then decomposes this 3-D model into a 2-D model with height that is averaged over a layer of fixed thickness. An asymptotic model is then formed and solved producing 2-D stream-functions and an equation for the velocity on the surface (which can then be inserted directly into the original spread model for the advection of heat around the fire).

Ferragut *et al*. (2007) present a simplified 2-D variation of this theme in which a numerical method of solving a set of governing equations (incorporating radiation, moisture content, wind and slope) using non-dimensionalised forms within a multivalued operator is employed. The effects of initial fuel moisture content and endothermic pyrolysis are explored. Wind is incorporated via the empirical relation of Simeoni *et al*. (2002). A finite element method is used to solve discretised forms of the governing equations. The authors found the computational cost of the radiation component to be high (in the order of 20 times that of the rest of the model), leading the authors to endeavour to simplify the radiation model in order to achieve better than real-time computation speeds. Comparison with experimental results of Mendes-Lopes *et al*. (1998) up to wind speeds of $2\ m\ s^{-1}$ found good correlation. Difficulties dealing with highly turbulent flows at wind speeds $>3\ m\ s^{-1}$ precluded model comparison.

This model shows some potential for operational use but remains only of research interest owing to the dimensional limitations.

UoC-R (University of California, Riverside, USA)

Zhou and Pereira (2000) developed a 2-D physical model (x and z) that assumed the fuel bed was a porous medium with a randomly orientated discrete solid matrix. Conservation of mass,

momentum, energy and species for both the gas and solid phase were formulated and a κ–ε eddy viscosity model of turbulence extended to buoyancy effects and flow through the fuel bed. Fuel is assumed to undergo volatilisation at a rate based on the thermokinetics of a small coal particle. Combustion is modelled on the eddy-dissipation concept model in which the combustion reaction rate is taken to be the slowest of turbulence dissipation rates; heat is assumed to come from gas-phase oxidation only and heat of volatilisation and evaporation are assumed to be negligible compared with heat liberated from the volatile gas. Radiation is modelled using the discrete ordinates method for an interacting grey medium. Soot formation is modelled as an average soot volume fraction and is assumed to form as a result of volatilisation. The governing equations were solved using the finite volume method on an orthogonal grid of 63×39 cells. The computational domain measured 1.23 m high by 2.03 m long. The time step was 0.25 s. Numerical results were compared with a series of laboratory experiments burning needles of *Pinus canariensis* and found to slightly overpredict ROS by ~10–20%.

A revised version (Zhou *et al*. 2005*a*, 2005*b*) refined the computation grid (129×65 non-uniform cells covering a computational domain of 4.0 m in length and 3.5 m in height with a fuel bed represented by 51×16 cells covering a domain 1.3 m long and 0.4 m high), the representation of the fuel, and incorporated additional species transport. Combustion and turbulence models remain the same. This model is compared with a series of experiments aimed at determining marginal burning in live chaparral fuels. Chaparral fuel was modelled as two components: foliage and branches, defined by different surface area to volume ratios, represented as cylinders for convective heat transfer purposes. Water vaporisation, pyrolysis of solid fuel to gas phase, char formation and oxidation were also incorporated, as well as the ability to include the effects of fuel bed arrangement, slope and environmental conditions.

Zhou *et al*. (2007) extended the model to 3-D and employ the Large Eddy Simulation (LES) method to model the spread of fire through the fuel bed using a subgrid turbulent combustion model based on a flame surface density concept, in which the volatilised gas is assumed to be a mixture of species (Zhou and Mahalingam 2001). The 3-D grid consisted of $62 \times 62 \times 62$ uniform cells over a computational domain measuring $1.2 \times 1.2 \times 1.2$ m. Two minutes of simulation time took 3 weeks on a 2.0 GHz Unix workstation. The model was used to investigate the effect of slope on the fire dynamics and on the marginal burning of chaparral fuels. It was found that the convective heat transfer induced by the interaction of the fire and slope was the dominant process in the spread of the fire.

This model has limited operational potential but has been used extensively for research purposes.

WFDS (National Institute of Science and Technology, USA)

The Wildland Fire Dynamics Simulator (WFDS) (Mell *et al*. 2007) is an extension of the Fire Dynamics Simulator (FDS), a model developed to predict the spread of fire within structures. This model is fully 3-D, is based on a unique formulation of the equations of motion for buoyant flow (Rehm and Baum 1978) and is intended for use in predicting the behaviour of fires burning through peri-urban/wildlands (what the authors call 'community-scale fire spread' (Evans *et al*. 2003; Rehm *et al*. 2003)). The main objective of this model is to predict the progress of fire through predominantly wildland fuel augmented by the presence of combustible structures.

WFDS utilises a varying computational grid to resolve volumes as low as 1.6 (x) × 1.6 (y) × 1.4 (z) m within a simulation domain in the order of 1.5 km^2 in area and 200 m high. Outside particular regions of interest, the grid resolution is decreased to improve computation efficiency.

Mell *et al*. (2007) give a detailed description of the WFDS formulated for the specific initial case of grassland fuels in which vegetation is not resolved in the gas-phase (atmosphere) grid but in a separate solid-fuel (surface) grid (which the authors admit is not suitable for fuels in which there is significant vertical flame spread and air flow through the fuel). Momentum drag, caused by the presence of the grass fuel (modelled as cylinders) and which changes over time as the fuel is consumed and calculated in the solid-fuel grid, is represented in the gas-phase grid. Mechanical turbulence, through the dynamic viscosity of the flow through the fuel, is modelled as a subgrid parameter via a variant of the LES method.

The WFDS assumes a two-stage endothermic thermal decomposition (water evaporation and then solid fuel pyrolysis). It uses the temperature-dependent mass loss rate expression of Morvan and Dupuy (2004) to model the solid fuel degradation and assumes that pyrolysis begins at 400 K. Solid fuel is represented as a series of layers that are consumed from the top down until the solid mass reaches a predetermined char fraction at which point the fuel is considered consumed.

WFDS assumes combustion occurs solely as the result of fuel gas and oxygen mixing in stoichiometric proportion (and thus is independent of temperature). Char oxidation is not accounted for. Owing to the relatively coarse scale of the resolved computation grids within WFDS, detailed chemical kinetics are not modelled. Instead, the concept of a mixture-fraction within a resolved volume is used to represent the mass ratio of gas-phase fuel to oxygen using a fast chemistry or flame sheet model that then provides the mass loss flux for each species. The model assumes that the time scale of the chemical reactions is much shorter than that of mixing.

Thermal radiation transport assumes a grey gas absorber–emitter using the finite volume method for which the absorption coefficient is a function of the mixture-fraction and temperature for a given mixture of species. A soot production model is not used; instead, it is an assumed fraction of the mass of fuel gas consumed based on empirical data.

Mell *et al*. (2007) provide simulation information for two experimental grass fires. In the first case of a high-intensity fire in a plot 200×200 m within a domain of 1.5×1.5 km and vertical height of 200 m represented by a total of 16 million grid cells, the model (running on a computer with 11 processors) took 44 processor hours for 100 s of simulated time. Another lower-intensity experiment over a similar domain took 25 processor hours for 100 s of simulated time. Although this model is not suitable for operational fire spread prediction owing to the computational requirements, its detailed consideration of fuel, combustion and heat transfer mechanisms make it highly suitable for planning and research purposes.

Table 3. Quasi-physical models published in the literature 1990–2007
Planes of movement are: *x*, direction of spread or mean wind; *y*, horizontally perpendicular to direction of spread; and *z*, vertical

Model	Author (Year)	Origin	Dimensions	Plane
ADFA I	de Mestre *et al*. (1989)	Australia	1	*x*
TRW	Carrier *et al*. (1991)	USA	2	*xy*
Albini	Albini *et al*. (1996)	USA	2	*xz*
UdC	Santoni *et al*. (1998)	France	2	*xy*
ADFA II	Catchpole *et al*. (2002)	Australia; USA	2	*xz*
Coimbra	Vaz *et al*. (2004)	Portugal	2	*xy*
UoC-B	Koo *et al*. (2005)	USA	2	*xz*

Quasi-physical models

This section briefly outlines quasi-physical models that have appeared in the literature since 1990 (Table 3). The model of de Mestre *et al*. (1989) is included because it was missed by previous reviews and provides the basis for a subsequent model. Similarly, Albini (1985) and Albini (1986) are included because later models derive from these works.

The main feature of this form of model is the lack of combustion chemistry and reliance on the transfer of a prescribed heat release (i.e. flame geometry and temperature are generally assumed). They are presented in chronological order of publication.

ADFA I (Australian Defence Force Academy, Australia)

de Mestre *et al*. (1989) developed a physical model of fire spread based initially only on radiative effects, in much the same way as that of Albini (1985, 1986) (see below) but in a much simplified manner.

The authors utilised a conservation of heat approach to model the spread of a planar fire of infinite width across the surface of a semi-transparent fuel bed in a no-wind, no-slope situation. However, unlike Albini, who modelled the fuel bed in two dimensions (i.e. *x* and *z*), de Mestre *et al*. chose to model only the top of the fuel bed, arguing that it is this component of the fuel bed that burns first before burning down into the bed; thus this model is one-dimensional (in *x*) plus time.

Assumptions included vertical flames that radiate as an opaque surface of fixed temperature and emissivity, a fixed fuel ignition temperature, and radiation from the combustion zone as an opaque surface also of fixed temperature and emissivity. Here, they also assumed that the ignition interface in the fuel bed is a linear surface, as opposed to Albini's curved one, in order to simplify the computations.

Two approaches to the vaporisation of the fuel moisture were modelled – one in which it all evaporates at 373 K (i.e. three-stage model ($<$373 K, 373 K, $>$373 K)), and one in which it evaporates gradually below 373 K (two-stage model ($\leq$373 K, $>$373 K)).

The final model included terms for radiation from flame, radiation from combustion zone, radiative cooling of solid fuel, and convective cooling of solid fuel. Without the cooling terms, the model was found to overpredict ROS by a factor of 13. A radiative cooling factor brought the overprediction down to a factor of 9. Including a convective cooling term to the ambient air apparently brought the prediction down to the observed ROS but this was not detailed.

No performance data are given. This model may be of academic interest.

TRW (TRW Inc., USA)

Carrier *et al*. (1991) introduced an analytical model of fire spread through an array of sticks in a wind tunnel. Unlike many preceding fire-modelling attempts, they did not assume that the dominant preheating mechanism is radiation, but a mixture of convective/diffusive (what they called 'confusive') heating.

Predominately concerned with deriving a formula for the forward spread of the fire interface in the wind tunnel (based on a series of experiments conducted and reported by Wolff *et al*. 1991), Carrier *et al*. assumed that the fire achieves a 'quasi-steady' ROS in conditions of constant wind speed and fuel conditions. They made the point that, at the scale they are concerned with, the spread can be viewed as continuous and can thus involve a catch-all heat-transfer mechanism (gas-phase diffusion flame) in which radiation plays no part and it is the advection of hot gas from the burned area that preheats the fuel (assuming all of it is burnt).

The model is two-dimensional in the plane *xy* for which it is assumed there is no lateral difference in the spread of the fire (which is different to assuming an infinite-width fire). Indeed, their formulation actually needs the width of the fuel bed *and* the width of the wind tunnel. The fluctuating scale of the turbulence within the tunnel is incorporated in a scale length parameter. Air flow within the fuel bed is ignored.

Using a first-principles competing argument, they argue that if radiation was the source of preheating, the estimate of radiant energy ($2.9\,J\,g^{-1}$) ahead of the fire would fall well short of the $250\,J\,g^{-1}$ required for pyrolysis. A square root relation between wind speed normalised by fuel load consumed and rate of forward spread was determined and supported by experimental observation (Wolff *et al*. 1991). Carrier *et al*. (1991) suggest that only when fuel loading is very high (on the order of $2\,kg\,m^{-2}$) will radiative preheating play a role comparable with that of convective/diffusive preheating.

No performance data are given. This model is not suitable for operational use but is of academic interest.

Albini (US Forest Service, USA)

Albini (1985, 1986) developed a two-dimensional (in the plane *xz*) radiative model of fire spread through a single homogeneous fuel layer. The latter paper improved on the former by including a fuel convective cooling term. Both models required that flame geometry and radiative properties (temperature and emissive power) be prescribed *a priori* in order for the model to then determine, in an iterative process, the steady-state speed of the fire front. The fire front is considered to be the isothermal flame ignition interface between unburnt and burnt fuel expressed as an eigenvalue problem, utilising a three-stage fuel heating model (<373 K, 373 K, 373 K $\leq T_i$), where T_i is the ignition temperature of 700 K.

A modified version of this spread model incorporated a thermally inert zone, which allowed the passage of a planar flame front but did not influence the spread process, placed beneath the homogeneous fuel layer to simulate propagation of a fire through the crowns of the trees. It was tested against a series of field-based experimental crown fires conducted in immature jack pine (Albini and Stocks 1986). The results from one experimental fire were used to parameterise the model (flame radiometric temperature and free flame radiation) and obtain flame geometry and radiative properties for the remaining fires. The model was found to perform reasonably well, with a maximum absolute percentage error of 14%.

Albini (1996) extended the representation of the fuel to multiple levels, where surface fuel, subcanopy fuel and the canopy fuel are incorporated into the spread model. The fuel complex was transcribed into a vertical series of equivalent single-component (homogeneous) surrogate layers based on weighted contributions from different fuel components (e.g. surface–volume ratio, packing ratio) within a layer. Albini also introduced a closure mechanism for removing the *a priori* requirement for flame geometry and radiative properties. The closure method involves the positing of a 'trial' ROS, along with free flame geometry and ignition interface shape, that are then used to predict a temperature distribution within the fuel. This distribution is then subsequently used in a submodel to refine the fire intensity, ROS, flame geometry, etc. This continues iteratively until a convergence of results is achieved. A quasi-steady ROS is assumed and the temperature distribution is assumed stationary in time. A conservation of energy argument, that the ROS will yield a fire intensity that results in a flame structure that will cause that ROS, is then used to check the validity of the final solution.

Butler *et al*. (2004) used the heat transfer model of Albini (1996) in conjunction with models for fuel consumption, wind velocity profile and flame structure, to develop a numerical model for the prediction of spread rate and fireline intensity of high-intensity crown fires. The model was found to accurately predict the relative response of fire spread rate to fuel and environment variables but significantly overpredicted the magnitude of the speed, in one case by a factor of 3.5. No performance data are given but this model may be suitable for operational use, depending on input data requirements.

UdC (University of Corsica, France)

UdC (Santoni 1998; Santoni and Balbi 1998; Balbi *et al*. 1999) is the result of a concerted effort to develop a physical model of fire spread that would be suitable for faster than real-time operational use. The initial approach was a quasi-physical model in which the main heat transfer mechanisms were combined into a so-called 'reactive diffusion' model, the parameters of which were determined experimentally.

The main components of UdC are a thermal balance model that incorporates the combined diffusion of heat from the three heat transfer mechanisms and a diffusion flame model for determination of radiant heat from flames. The heat balance considers heat exchanged with the air around a fuel cell, heat exchanged with the cell's neighbours, and heat released by the cell during combustion. It is assumed that the rate of energy release is proportional to the fuel consumed and that the fuel is consumed exponentially. The model is two-dimensional in the fuel layer (the plane *xy*). No convection, apart from convective cooling to neighbouring cells is taken into account, nor is turbulence. Model parameters were determined from laboratory experiments.

Initially, radiation from the flame was assumed to occur as surface emission from a flame of height, angle and length computed from the model and an isothermal of 500 K. Flame emissivity and fuel absorptivity were determined from laboratory experiments in a combined parameter. The early version of the model was one-dimensional for the fuel bed (x) and two-dimensional (x and z) for flame. Forms of the conservation of mass and momentum equations were used to control variables such as gas velocity, enthalpy, pressure and mass fractions.

Santoni *et al*. (1999) presented a 2-D version of the model in which the radiative heat transfer component was reformulated such that the view factor, emissivity and absorptivity were parameterised with a single value for each fuel and slope combination that was derived from laboratory experiments. This version was compared with experimental observations (Dupuy 1995) and the radiation-only models of Albini (1985, 1986) and de Mestre *et al*. (1989) (Morandini *et al*. 2000). It was found to predict the experimental increase in ROS with increasing fuel load much better than the other models but tended to underpredict under higher wind speeds and slopes (Morandini *et al.* 2001*a*). The UdC model also outperformed the other models on slopes but this is not surprising as it had to be parameterised for each particular slope case.

Simeoni *et al*. (2001*a*) acknowledged the inadequacies of the initial 'reaction-diffusion' model and Simeoni *et al*. (2001*a*, 2001*b*, 2002, 2003) undertook to improve the advection component of the UdC model by reducing the physical modelling of the advection component of the work of Larini *et al*. (1998) and Porterie *et al*. (1998*a*, 1998*b*) to two dimensions to link it to the UdC model. It occurred in two parts: one as a conservation of momentum component that was included in the thermal balance equations (temperature evolution), and one as a velocity profile through the flaming zone. They assumed that buoyancy, drag and vertical variation were equivalent to a force proportional to the quantity of gas in the multiphase volume and that all the forces were constant whatever the gas velocity. The net effect was that the horizontal velocity decreases through the flame to zero at the ignition interface and does not change with time. Again, the quasi-physical model was parameterised using a temperature–time curve from a laboratory experiment with no wind or slope. The modified model improved the performance only marginally, particularly in the no-slope case, but still underpredicted ROS.

Morandini *et al*. (2001*a*, 2001*b*, 2002) attempted to address the inability of the original formulation to properly account for fuel preheating by improving the radiant heat transfer mechanism of the model to include non-local radiation. Surface emission from a vertical flame under no-wind conditions was assumed and a flame tilt factor included when under the influence of wind. The radiation transfer equation used a view factor of the flame in which it was simplified to the sum of vertical panels of given width. The length of each panel was assumed to be equal to the flame depth, mainly because flame height is not modelled. In cases of combined slope and wind, it was assumed that the effects on flame angle are independent of slope. Morandini *et al*. (2002) approximated the effects of wind speed by an increase in flame angle in a manner similar to terrain slope by taking the inverse tangent of the flame angle of a series of experiments divided into the mid-flame wind speed. This was then considered a constant for a range of wind speeds and slopes. Again, the model was parameterised using a laboratory experiment in no-wind, no-slope conditions. Results are given for a range of slopes ($-15°$ to $+15°$) and wind speeds (1, 2, 3 m s^{-1}). The prediction in no wind and slope was good, as were the predictions for wind and no slope. The model broke down when slope was added to high wind (i.e. 3 m s^{-1}). Here, however, they determined that their model only worked for equivalent flame tilt angles (i.e. slope and wind angles) up to 40 degrees.

Morandini *et al*. (2005) combined the previous efforts of radiation and advection modelling into a model capable of simulating spread under both wind and slope. The model was computed on a fine-scale uniform grid using a finite difference method with an implicit scheme and solved using the iterative Jacobi method, and the gas-phase equations solved using a fourth-order Runge–Kutta method. The grid size was 0.01 m and the time step was in the range 0.01–0.002 s. The model was compared with two sets of laboratory experiments (representing no slope and no wind and combinations of wind and slope). The model was found to predict combinations of low wind speeds and low slope well but tended to overpredict at higher wind speeds and slopes. This was attributed to the model's inability to account for 'random' flame contact with the fuel – thought to be a result of a mixed-flow boundary layer induced by turbulent flow above the fuel bed. They found that the model produced a greater contribution from radiation than convection by a factor of two or more.

No performance data for the later model are given; however, an earlier version on a Sun Ultra II workstation was described by Santoni (1998) as taking 114 s to compute 144 s of simulation. When the domain was reduced to just the fire itself, the time was reduced to 18 s. This model, owing to its restricted computational domain and limited fuel representation is of academic interest but could provide the basis of an operational model.

ADFA II (Australian Defence Force Academy, Australia)

Catchpole *et al*. (2002) introduced a much-refined version of ADFA I (de Mestre *et al*. 1989), here called ADFA II. Like ADFA I, it is a heat-balance model of a fuel element located at the top of the fuel bed. The overall structure of the model is the same, with radiative heating and cooling of the fuel (from both the flames and the combustion zone), and convective heating and cooling. It is assumed that the flame emits as a surface but one in which the emissive power varies with height above the fuel. They use laboratory experiments to determine the emissive energy flux based on a Gaussian vertical flame profile and a maximum flame radiant intensity derived from the fireline intensity. The model assumes infinite width for the radiative emissions.

Combustion zone radiation is treated similarly. Byram's convective number (Byram 1959*b*) and fireline intensity (Byram 1959*a*) are used to determine flame characteristics (angle, height, length, etc.). Empirical models are used to determine gas temperature profile above and within the fuel as well as maximum gas temperature, etc. ADFA II utilises an iterative method to determine ROS, similar to that of Albini (1996), assuming that the fire is at a steady-state ROS.

No performance data are given. Owing to its low dimensionality, this model is only of academic interest.

Coimbra (Polytechnic Institute of Coimbra, Portugal)

The aim of Vaz *et al*. (2004) was not to develop a new model of fire spread as such, but to combine the wide range of existing models in such a way as to create a seamless modular quasi-physical model of fire spread that can be tailor-made for particular situations by picking and choosing appropriate submodels. The 'library' of models from which the authors pick and choose their submodels are classified as: heat sink models (including Rothermel 1972; Albini 1985, 1986; de Mestre *et al*. 1989), which consider the conservation of energy aspects of fuel heating and moisture loss and ignition criteria; heat flux models (including Van Wagner 1967; Albini 1985, 1986), which consider the net exchange of radiative energy between fuel particles; and heat source models (including Thomas 1967, 1971), which consider the generation of energy within the combustion zone and provide closure for the other two types of models.

The authors compared a fixed selection of submodels with data gathered from a laboratory experiment conducted on a fuel bed 2 m wide by 0.8 m long under conditions of no wind and no slope. The set of models was found to underpredict ROS by 46%. This was improved to 6% when observed flame height was used in the prediction. Predicted flame height, on which several of the submodels depend directly, did not correspond with observations, regardless of the combination of submodels selected. Rather than producing a fire behaviour prediction system that utilises the best aspects of its component models, the result appears to compound the inadequacies of each of the submodels. None of the three classes of submodels consider advection of hot gases in the heat transfer.

No performance information is given. Depending on the method of implementation of the submodels, this may be of operational use.

UoC-B (University of California, Berkeley, USA)

Koo *et al*. (2005) modified the model of Pagni and Peterson (1973) and Pagni (1975) and tested it against a series of laboratory and field experiments. The model uses a heat balance approach to account for heat transfer into and out of a porous, thermally thin (i.e. no vertical temperature gradient within the fuel bed) layer. Heat transfer is assumed to occur by radiation from the flames, by radiation from adjacent burning fuel elements in the fuel bed, from radiative cooling to the ambient

surrounds, from forced convection above the fuel bed (from both ambient wind and heated gases) and from convection within the fuel bed. Ignition of the fuel element occurs when it reaches a predetermined ignition temperature. The amount of energy required to achieve this temperature is determined using the proviso of steady-state ROS and the energy needed to maintain the ignition temperature at the base of the flames as it moves across the fuel bed. Energy from a fuel element is lost by the evaporation of moisture from the element.

The flame is assumed to be an isothermal surface emitter with an emissivity approximated from the flame length and an absorption coefficient of $0.6\ m^{-1}$. The view factor for the top of the fuel element incorporates a function for a finite-width fuel bed. Radiation from embers within the fuel bed is assumed to decay exponentially with distance from the flame base and the absorption into the fuel element is a function of the fuel's surface area to volume ratio. Radiative cooling is a function of the fuel temperature and the fuel bed depth. Convective heat transfer ignores the effects of buoyancy. Depending on the mode of spread (backing or forward spread, up or down slope), convective transfer can cool or heat the fuel element, and is modelled as a function of the Reynolds number of the flow using different length scales for each mode of spread.

The model was compared with several series of experiments in different fuels, including white birch sticks and grass fuel beds in the laboratory and shrub understorey in a pine forest in the field. In each case, the model was found to provide reasonable quantitative agreement with observed values, although the authors note the limitation of measured fuel characteristics needed for the model.

No performance information on the model is provided. The authors suggest their model may play a role in the revision of operational models but neglect to mention how this may be achieved.

Discussion

The physical models discussed here (see Table 4) can be divided primarily into two types: those that are intended for simulation purposes (i.e. the application of the model to simulate the propagation of a fire across a surface, which may be of operational or research interest) and those that are intended to explore a particular physical process or aspect of the behaviour of wildland fires. The latter are generally characterised by low spatial dimensionality (i.e. only 1- or 2-D), are analytical in nature, and are restricted in scope with respect to their computational domain. It is possible, however, that components of such models (e.g. Grishin) may later find their way into other models that might be used for simulation purposes. Sometimes the nature of the model itself dictates its potential use, rather than the authors' intention. Grishin and LEMTA were formulated with the intention of being of assistance in the operational prediction of fire spread but owing to the complex nature of these models (and the difficulty of obtaining solutions to the equations) or their reduced physical dimensionality, the models have not and most probably will not be used operationally. It is also possible to categorise physical models by their treatment of the flow field. Those that have a complete treatment of the flow are more likely

Table 4. Summary of physical models

DO, discrete ordinates; EDC, eddy dissipation concept; EV, eigenvalue; FD, finite difference; FE, finite element; FV, finite volume; LES, large eddy simulation; MF, mixture function; MiB, mixed-is-burnt; MRTE, multiphase radiation transport equation; RANS, Reynolds-averaged Navier–Stokes; RNG, renormalisation group; PDF, probability distribution function; P1, differential approximation; S2S, surface to surface

Model	Simulation?	Minimum resolution (Δm, Δs)	>Real time?	Multiphase?	Discretisation method	Solver method	Combustion chemistry	Combustion model	Turbulence model	Radiation model
Weber	No	–, –	–	Yes	–	–	–	–	None	–
AIOLOS-F	Yes	–, –	–	–	Hybrid FD	Implicit	?	MF	–	–
FIRETEC	Yes	2, 0.002	No	Yes	FE	–	2-step	PDF	RANS	–
Forbes	No	–, –	–	No	–	–	1-step	–	None	None
Grishin	No	–, –	–	Yes	–	–	2-step	–	–	–
IUSTI	Yes	0.3, 0.025	No	Yes	Non-uniform FV	Euler	2-step	MiB	RNG κ–ε	MRTE
PIF97	No	0.003, ?	No	Yes			2-step	MiB	–	P1
FIRESTAR	No	0.025, 1	No	Yes	FV	Implicit	2-step	EDC	RNG κ–ε	DO
LEMTA	No	–, –	No	Yes	–	EV	1-step	–	–	S2S
UoS	No	1.8, 0.25 μs	–	No	–	–	1-step	–	–	–
UoC-R	No	0.02, –	No	Yes	FV		2-step	–	LES	DO
WFDS	Yes	1.5, –	No	Yes	FV	Runge–Kutta	2-step	MF	LES	FV

Table 5. Summary of quasi-physical models
Equivalent surface radiative temperature, assuming emissivity = 1

Model	Simulation?	Primary mechanism	Radiation type	Equivalent surface radiative temperature (K)	Turbulence?
ADFA I	No	Radiation	Surface	795	No
TRW	No	Convection/Diffusion	Volume	–	Yes
Albini	Yes	Radiation	Surface	1050	No
UdC	Yes	Radiation/Convection	Surface	970	Yes
ADFA II	No	Radiation/Convection	Surface	–	Yes
Coimbra	Yes	Mix	Surface	1100	–
UoC-B	No	Radiation/Convection	Surface	1083	No

to be of a simulation nature (e.g. FIRETEC, IUSTI, WFDS) than those that do not (e.g. Weber, Forbes).

Of those physical models that were intended for fire spread simulation applications, only AIOLOS-F, FIRETEC, FIRESTAR, IUSTI and WFDS have been applied to large-scale 'landscape'-type domains. The other models, UoS and UoC-R, have so far only been applied to small-scale 'laboratory' domains. All (with the exception perhaps of AIOLOS-F) are characterised by extended and ongoing development and publication. FIRETEC and WFDS are relatively unique in that they were originally formulated for full 3-D simulation of fire spread at the 'landscape' scale. Others, such as FIRESTAR and IUSTI, which commenced as 2-D formulations at the laboratory scale, have progressed (or are progressing) to full 3-D versions and larger computational domains. All four of these models have necessarily detailed fuel descriptions to better represent wildland fuels. In contrast, LEMTA, which was originally formulated as full 3-D, has been reformulated to 2-D to improve computational feasibility.

The quasi-physical models discussed here (see Table 5), for the most part, are designed for use in a 'laboratory'-scale domain and as such not suitable for landscape simulation, primarily because of their plane of prediction (i.e. vertical plane rather than horizontal plane). Albini, ADFA II and UoC-B can only predict the forward ROS of a fire and, although they may have the potential for replacing existing operational ROS systems (which currently do only predict the rate of forward spread), have not been implemented in this manner. Of the three models capable of predicting spread across the horizontal plane, none have been formulated for use in an operational context, although both UdC and Coimbra have this potential; TRW is limited to the context of a wind tunnel and predefined fuel arrangement.

The following sections raise and discuss several key aspects involved in the design, formulation, implementation and use of physical and quasi-physical models of fire spread. Where information is not available or an item is not applicable in Tables 4 and 5, a dash (–) is assigned.

Formulations, simplifications and solutions

The primary task in building a physical model of a phenomenon is the identification of the governing processes involved in the phenomenon. This is then followed by the formulation of mathematical equations that describe these processes such that they can be solved in order to provide a prediction of the behaviour of the processes. In the case of wildland fire, these tasks are by no means simple. The broad scope of possible processes (from chemical reactions to heat and mass transfer in the atmosphere), the spatial and temporal range of the processes involved, and the possible interaction of the processes, mean that capturing all the processes involved at all the scales involved is quite difficult. Generally, the fundamental laws of nature are used to derive the governing equations for each process but there are a variety of ways of formulating such equations, each with a range of suitable applications and domains.

However, often the full formulation of the governing equation for a process is not computationally feasible and so simplified forms are used. Simplifications for incompressible and inviscid flows (in which viscous forces are ignored) are often employed. Some aspects of flow, such as turbulence, can be ignored (e.g. laminar flow is assumed) but are increasingly included in simplified form. Although direct numerical simulation (DNS), which explicitly computes everything up to and including the energy dissipation scales of turbulent flow, is possible, it is costly in terms of computation as well as time (indeed, a full numerical solution to turbulent atmospheric flow with Reynolds number in the order of 60 000–90 000 would take decades on the current computer hardware (Jiménez 2006)). As a result, several approximate models have been developed to include the effects of turbulent flow. These include the Reynolds-averaged Navier–Stokes (RANS) method, in which the solution variables in the instantaneous (exact) Navier–Stokes equations are decomposed into the mean (ensemble-averaged or time-averaged) and fluctuating components; and the LES method, which explicitly computes large-scale eddies directly but treats the dissipation and inertial cascade at smaller scales using sub-grid-scale approximations. The RANS method is not closed owing to use of unknown Reynolds stress terms and must be closed through estimated eddy viscosities (such as the κ–ε method involving the evolution of fluctuating kinetic energy (κ) and eddy dissipation (ε) (Jiménez 2006)), for which rigorous statistical methods such as renormalisation group theory (RNG) (Yakhot and Orszag 1986) have been used to lead to improved formulations, or Reynolds stress evolution methods (known as the Reynolds stress transport model (RSM) (Launder *et al*. 1975)),

in which the RANS equations are closed by equations for the Reynolds stresses.

FIRETEC uses the RANS RSM method, IUSTI and FIRESTAR use the RNG κ–ε method whereas WFDS and UoC-R use the LES method. Each method has its advantages and disadvantages in terms of computational cost, efficiency and accuracy. 3-D formulations are inherently more computationally costly. Some formulations require the solution of additional equations or access to additional memory, which increase computational cost. Quasi-physical models often do not explicitly include turbulence in their formulations, instead including the effects implicitly in the convective mixing of heated gas with unburnt fuel. This is the case for ADFA I and II, Albini and UoC-R. TRW and UdC both incorporate turbulence in the formulation for heat transfer.

Often the governing equations of physical models are formulated as partial or ordinary differential equations that are not conducive to analytical solutions and must be solved by numerical methods. By their nature, differential equations are continuous and thus must be discretised (that is, a method of approximating the differential equation such that a suitable system of algebraic equations for the variables can be solved at some set of discrete locations in space and time (Ferziger and Perić 1996)). Common methods for discretisation are finite difference (FD), finite element (FE) and finite volume (FV) (but may also include spectral schemes and cellular automata, which are limited to certain classes of problems). The domain of the solution is divided into a structured grid of nodes (which may be regular or irregular) based on a suitable coordinate system. The primary difference between the methods is the technique in which the algebraic approximation is applied to the nodes of the grid and the approach used to incorporate the neighbouring nodes in determining the unknowns of the governing equations. Each method has its advantages and disadvantages and for the most part the physical models discussed here use the FE method (Table 4) with various methods of applying the grid (e.g. most models apply varying resolution grids to reduce computational costs in regions where combustion will not occur). Quasi-physical models are often presented in the form of linear differential equations (in some cases, such as TRW, can be presented in the form of an analytical solution) and as such are solved by iterative methods with a corresponding decrease in computational costs.

A key attribute of a physical fire spread model in comparison with a generic fluid dynamics flow model is the presence of combustion chemistry, which releases heat into the system. In all cases, the chemistry of the combustion of biomass fuel is simplified and idealised as the detailed chemical kinetics involved is highly complex and computationally expensive (Di Blasi 1993). Of the physical models suitable for simulation, IUSTI and FIRESTAR (both derived from the work of Grishin) present the most complex combustion chemistry by considering several combustion reactant and product species; however, as with Grishin, these are simplified in the gas phase to the combustion of CO. In these cases, a two-step, two-path parallel chemical reaction is modelled in which volatile gas is formed in parallel with char from solid fuel and then both oxidised in flaming combustion. The latest version of FIRETEC incorporates a two-path gas-phase-only combustion process for flaming combustion. The remaining models use a single-step chemical reaction in which an idealised fuel undergoes direct oxidation. No model considers the competitive formation of char and volatiles (Ball *et al*. 1999).

Several techniques are employed in the physical models to then model the rate of combustion of the pyrolysation products. WFDS and UoC-R use the mixture-fraction (MF) method where it is assumed that the reactants are brought together in stoichiometric proportion and that the chemistry time scale is much shorter than that of mixing, resulting in combustion that is independent of temperature (i.e. mixed-is-burnt (MiB)). PIF97 uses a similar 'mixed-is-burnt' technique. FIRETEC uses a probability distribution function (PDF) for the distribution of temperature within the resolved volume to determine when combustion occurs. IUSTI and FIRESTAR use the eddy dissipation concept (EDC) model in which reaction rates are controlled by the rate of turbulent mixing, in which the reactions occur in small turbulent structures.

Similarly, several models are employed to incorporate radiation from combusting gases. FIRESTAR and UoC-R employ the discrete ordinates (DO) method, which solves the radiation transfer equation as a transport equation for a finite number of discrete solid angles and which can be used over a wide range of optical thicknesses, in participating media and for surface exchange. IUSTI uses a unique radiation model called the multiphase radiation transport equation (MRTE) (Consalvi *et al*. 2002). WFDS uses the FV method, which solves the grey gas form of the radiation transfer equation in a participating media. PIF97 employs the differential approximation method, in which grey radiation is assumed and all surfaces are considered diffuse; it is less accurate when the optical thickness of the medium is small. LEMTA employs the surface to surface (S2S) model, which accounts for radiation exchange between grey-diffuse surfaces but does not include scattering. All the quasi-physical models, with the exception of TRW, treat radiation as a surface emission and use a simplified uniform isothermal flame sheet as the radiation source (ADFA II does allow a vertical Gaussian profile in the flame temperature). The temperatures of this surface vary from model to model.

The result of discretisation of the governing differential equations is a set of non-linear algebraic equations, the method of solution of which depends on the nature of the problem. Generally, physical models of fire are unsteady flows and thus use methods based on the initial value problem for ordinary differential equations. Often these methods rely on linearisation techniques to allow iterative solution techniques. Techniques of the models discussed here include methods based on Runge–Kutta (WFDS) or Euler's method (IUSTI, FIRESTAR). Each method has its relative advantages and disadvantages and is generally selected for the range of problems being considered by the model authors. Solution parameters such as time step and grid resolution determine the ability of the solver method to properly solve the set of equations and thus provide a useable solution. Too large a time step or grid resolution can result in divergence in the solution (in which the residual of the solution at each iteration does not decrease) and numerical instability, which result in incorrect solutions. Thus, there is a trade-off between the computation time and the accuracy of the solutions. None of the physical models for which simulation time information was given in the

literature are faster than real time and in some cases are several orders of magnitude slower than real time, even on relatively large supercomputers.

The requirements for data vary greatly between the physical and quasi-physical models. Generally, owing to the greater complexity of the physical models, a greater degree of information (e.g. model parameters, initial conditions and boundary conditions) is needed than that of the quasi-physical models. IUSTI, FIRESTAR and WFDS endeavour to provide solutions not only for the fire but also for the atmosphere around the fire, albeit at a much reduced resolution. FIRETEC, however, recognises the importance of the larger atmospheric conditions and thus utilises the results of a larger atmosphere model (HIGRAD) to provide the boundary conditions for the fire model.

Validation

The 'laboratory'-scale models are generally characterised by a close relation to complementary validation work in the laboratory with an associated simplified fuel (generally idealised beds of needles or other similarly homogeneous fuel), although UoC-R has been extended to more complex fuel beds. In many laboratory experiments, the standard condition is one of no wind and no slope. Although wildland fires in flat terrain do occur, it is very rare (if not impossible) for these fires to occur in no wind. The ability to correctly model the behaviour of a fire in such conditions is only one step in the testing of the model. The early versions of both IUSTI and FIRESTAR (as well as several the quasi-physical models discussed here) were found wanting in conditions other than no wind and slope, leading to significant revisions.

Validation for the larger domain simulation models is problematic. Morvan *et al*. (2004) argue that purely theoretical modelling with no regard for field observations is of less use than a field-based model for one particular set of circumstances. Although validation against fire behaviour observed in artificial fuel beds under artificial conditions provides useful information about the performance of a model, it does not test the ability of the model to capture those important processes involved in the behaviour of wildland fires. However, comparison with wildfires is very nearly impossible. Boundary conditions are rarely known and other quantities are almost never measured at the site of the fire itself; mapping of the spread of wildfires is haphazard and highly subjective in many instances. Thus, comparison with large-scale field experiments, although not necessarily representative of high-intensity wildfire conditions, does provide the complete set of interactions between fire, fuel, atmosphere and topography and is not to be understated. However, as is the case with any field experiment, it is very difficult to measure all required quantities (or, indeed, to control the range of most variables) to the degree of precision and accuracy required by the models.

WFDS, FIRETEC and FIRESTAR have all used a unique set of large-scale field experiments conducted in grasslands (Cheney *et al*. 1993) for validation purposes and thus avoided many of the issues of validation against wildfire observations. However, the issue of identifying the source of discrepancy in the results of such complicated models is just as difficult as obtaining suitable data against which to test the model. Both Linn *et al*. (2005) and Mell *et al*. (2007) identified significant deficiencies within their models (FIRETEC and WFDS, respectively) that only comparison with field observations could have revealed.

Of the quasi-physical models, only Albini and UoC-B have been tested against field experiments, although the authors of UdC have recently conducted a series of field experiments in shrub fuels (Morandini *et al*. 2006; Santoni *et al*. 2006). Generally, these models were developed using data from laboratory experiments and tested against either the same set of data or datasets of other authors who used similar experimental set-ups.

Summary

The present article has outlined the major physical and quasi-physical models of surface wildland fire spread that have appeared in the literature during the period 1990–2007. Physical models, based on the chemistry and physics of combustion and heat transfer, represent the state of the art of modelling in which the fundamental governing processes are employed to determine wildland fire behaviour. Quasi-physical models, based on the physics of heat transfer only, generally represent a simplification of the fundamental processes in which the amount of heat to be transferred is prescribed.

Physical models are characterised by their high computational (in terms of time, resources and data) requirements, which generally preclude their use as operational tools in wildfire management. Quasi-physical models, constructed from relatively less complicated formulations, are not necessarily any more computationally feasible than physical models and have their own limitations in terms of data and resource requirements.

Computational feasibility is of prime concern for those models that are intended to be used actively for fire management purposes. Although this is not necessarily the aim of the developers of the physical models discussed here – building a greater understanding of the processes involved in the behaviour of wildland fire is an often-cited aim – practical applications of these types of models is of great interest to many people; models such as AIOLOS-F, FIRETEC, WFDS and UdC stand out because of their stated aim to be a useful tool in fire management. Quasi-physical models, however, may not necessarily be more suited to operational use than the full physical models and, similarly, full physical models may not necessarily properly and completely capture all the physical processes involved in the behaviour of a bushfire.

Séro-Guillaume and Margerit (2002) suggested that computationally feasible models can be either constructed from simple models or reduced from complete models. Hanson *et al*. (2000) suggested that the operational fire behaviour models of the future will be reduced versions of the purely physical models being developed today. However, in all cases, the assumptions and simplifications of the governing processes necessary for computational feasibility in the context of operational use (as well as the numerical methods used to solve the set of equations) will reduce the confidence of end-users in the final result. The level of detail of data (type and resolution of parameters and variables) required for input into these models will not be generally available for some time and will necessarily have a high degree of imprecision. Additionally, any model will suffer from the same difficulties in validation against landscape-scale wildland fires.

Many authors of fully physical models are resigned to not being able to predict the behaviour of landscape wildland fires in better than real time and suggest that the primary use of such models is the study of fires under conditions, fuels and topographies that are not amenable to field experimentation. In an increasingly litigious social and political environment, this may be the only way to study large landscape-scale fire behaviour in the future, but this assumes that the physical model is complete, correct, validated and verified.

The basis for fire behaviour models of operational use is unlikely to be one of purely physical origin, simply because of the computational requirements to solve the necessary governing equations at the resolutions necessary to ensure model stability. It is most likely that for the foreseeable future operational models will continue to be empirical in origin. However, there may be a trend towards hybrid models of a more physical nature as the physical and quasi-physical models are further developed and refined.

Acknowledgements

I would like to acknowledge the CSIRO Sustainable Ecosystems Bushfire Dynamics and Applications (BDA) Team and the CSIRO Centre for Complex Systems Science for supporting the present project; Jim Gould and Rowena Ball for comments on the draft manuscript; Miguel Cruz and Stuart Matthews (BDA) and Grant Pearce (Scion, NZ) for internally reviewing the draft; and the anonymous journal referees who assisted in making this a much better article.

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Manuscript received 1 November 2006, accepted 13 March 2008