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REVIEW

A review of a new generation of wildfire–atmosphere modeling

A. Bakhshaii and E.A. Johnson

Abstract: One of the first significant developments in wildfire modeling research was to introduce heat flux as wildfire line intensity ($kW \cdot m^{-1}$). This idea could be adapted to using weather station measurements, topography, and fuel properties to estimate rate of fire spread, shape, and intensity. This review will present, in an accessible manner, the next evolution in wildfire models. The new generation models use mechanistic combustion models and large-eddy simulation (LES) to define the flaming combustion and the mechanism of rate of spread. These wildfire models are then coupled to a computational fluid dynamics (CFD) or mesoscale weather model. In other words, wildfire models become weather and climate models with add-in fuel and terrain models. These coupled models can use existing fire and weather physics or developed noncoupled models with a coupling mechanism. These models are tailored for specific spatial and temporal scales.

Key words: wildfire, fuel, fire behavior, WRF-FIRE, FIRETEC, WFDS, CAWFE, ForeFire/Meso-NH, ARPS/DEVS-FIRE, finite difference, finite volume.

Résumé : Un des premiers développements en recherche sur la modélisation des feux de forêt a été d'introduire le flux de chaleur en tant qu'intensité de la ligne de feu ($kW \cdot m^{-1}$). Cette idée pouvait être adaptée pour utiliser les mesures des stations météorologiques, la topographie et les propriétés des combustibles pour estimer la forme, l'intensité et le taux de propagation du feu. Cette synthèse présente de façon accessible la prochaine évolution dans les modèles de feux de forêt. La nouvelle génération de modèles utilise des modèles de combustion mécanistes et la simulation de grands écoulements tourbillonnants (LES) pour définir la combustion accompagnée de flammes et le mécanisme du taux de propagation. Ces modèles de feux de forêt sont ensuite couplés à un modèle de dynamique des fluides numérique (CFD) ou un modèle météorologique méso-échelle. En d'autres mots, les modèles de feux de forêt deviennent des modèles météorologiques et climatiques avec des modèles complémentaires de combustibles et de terrain. Ces modèles couplés peuvent utiliser un feu en cours et la physique météorologique ou des modèles non couplés avec un mécanisme de couplage. Ces modèles sont adaptés à des échelles spatiales et temporelles spécifiques. [Traduit par la Rédaction]

Mots-clés : feu de forêt, combustible, comportement du feu, modèles de simulation WRF-FIRE, FIRETEC, WFDS, CAWFE, ForeFire/Meso-NH, ARPS/DEVS-FIRE, différence finie, volume fini.

Introduction

Traditionally, the wildfire behavior community has had a goal of predicting fire spread and flame length from easily measured variables, particularly fuel and surface weather variables. Early fire behavior research was carried out by foresters and then by engineers working with foresters. For history of this era in Canada, see Van Wagner (1987*a*, 1987*b*), and for history in the United States (US), see Pyne (1984). This early approach was empirical. It started by measuring fuel moisture directly and then advanced to determining the drying rate of fuel by the correlation with observed weather station instrument values (Nelson 2001). The fuel was divided into categories dependent upon the vegetation and the size and arrangement of the fuel such as in the Canadian Wildland Fire Information System (CWFIS) and National Fire Danger Rating System (NFDRS). The traditional approach incorporated the heat from fuel consumption, but there was no differentiation of different types of heat transfer such as radiation and convection (e.g., Van Wagner 1967; Anderson 1969). The next development was in putting the fuel categories together with topography and the wind to predict fire spread (Brown 1974). Here again, the accent was on fire-line spread with idealized spread shapes and some understanding of combustion (Albini 1976). The focus was on behavior more than the mechanisms of combustion and heat transfer.

Underlying this approach was a semi-mechanistic framework (Byram 1959; Van Wagner 1965; Rothermel 1972; and others) that simplified the combustion and heat transfer of wildfires into a simple flux equation:

$$I = c(\mathrm{d}m/\mathrm{d}t) \quad (1)$$

where I is the heat output from the flaming front (fire intensity), c is the heat released per unit mass of fuel during combustion, and $\mathrm{d}m/\mathrm{d}t$ is the mass loss rate during flaming combustion. The formulation consists of three easily measured variables: the heat from combustion (c) determined by the main constituent of plant material, cellulose, and its moisture content; the mass lost during combustion of plant material; and the rate at which the fuel is fed into the flaming combustion, determined primarily by wind. This approach circumvented the more complete combustion and heat budget models and reduced mesoscale weather models to surface weather station data in a time when limited computing power was available. Three-dimensional spread, variation in fuel, and the exact coupling to atmospheric processes were simplified by

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two-dimensional geometry and statistical assumptions (Van Wagner 1987*a*). More importantly, the nonlinearity, interactions, and dimensionality were not included due to the focus on providing an easily executable method. Extreme fire events such as plume-driven fires, fire whirls, horizontal rolling vortices, fire combining with mountain winds, chimney fire, and fire-created winds (stronger than ambient wind speed) were never captured or could not be simulated by the traditional models due to the three-dimensional nature and vertical development of the phenomena (Van Wagner 1987*a*). Traditional fire behavior models do not consider the possibility of substantial feedbacks between the fire and the atmosphere. Heating from the fire produces buoyancy forces in the atmosphere and modifies near-surface winds, which can eventually increase the rate of fire spread and intensity. The buoyancy forces in a wildfire can increase the updraft by 1 to 2 orders of magnitude of an average thunderstorm (Lareau and Clements 2017). Using a scanning Doppler lidar and mobile radiosonde system during two large wildfires in northern California, Lareau and Clements (2016) found that compared with the ambient wind, the flow within the plume is characterized by much stronger velocities when outbound speeds exceeded 15 $m \cdot s^{-1}$ and the wind profiles showed significant shear over the lowest 2 km of the atmosphere. Lareau and Clements concluded, "The observed near-surface wind speed maximum is atypical in the atmospheric boundary layer and adverse wind profiles of this character have previously been linked to blow-up fires (Byram 1954)".

Traditional models are not always good at predicting the fire growth accurately due to the lack of feedback to the atmosphere (Pastor et al. 2003), particularly in recognizing the possibility that a fire will turn into a pyroconvective fire and have extreme changes in wind and moisture. The personal experience of fire experts has been more helpful in these cases than a traditional model prediction. These large fires account for the vast majority of the total area burned, and small fires (<100 ha) account for less than 1% of the area burned (Johnson et al. 1998; Stocks et al. 2002). One could also argue that uncertainty in weather forecasts could be responsible for reducing skill in fire growth prediction; however, it is understood that the traditional wildfire model cannot capture the complete process even with a more certain weather forecast (Lareau and Clements 2016, 2017).

The advancements in technology have transformed our understanding, observation, and prediction of weather and wildland fires. They also have changed our perspective to more mechanistically complete models of wildfire combustion and heat transfer and observations such as heat flux and aerosol observations from satellite images. The most recent developments have included more details of the weather at the scale of the fire front and its connection to larger scale weather mechanisms. In part, this change has been motivated by the need to understand fire spread in urban interface regions where there is a mixture of wildland fuels and built structures.

We will start by giving a general description of the more complete wildfire models as incorporated in FIRETEC (Linn et al. 2002), the Wildfire Dynamics Simulator (WFDS) (Mell et al. 2007), Coupled Atmosphere–Wildland Fire–Environment (CAWFE) (Clark et al. 1996*a*, 1996*b*, 2004; Coen 2005), Wildland Fire Module combined with the Weather Research and Forecasting numerical weather prediction system (WRF-FIRE) (Patton and Coen 2004; Mandel et al. 2011; Coen et al. 2013), ForeFire/Meso-NH (Filippi et al. 2011), and ARPS/DEVS-FIRE (Dahl et al. 2015). Next, we will discuss the model fluxes, domains, coupling (interaction), and numerical techniques. Finally, we will discuss some of the advantages and new approaches that these models provide.

Wildfire models — new generation

The first generation of wildfire models was divided into two main approaches: empirical and physical. The most distinguishing attribute of a fully physical model of fire behavior in comparison with empirical models is the presence of combustion chemistry, heat transfer, and fluid dynamics (Sullivan 2008). These models determine the heat, mass, and momentum fluxes released from the burn that are transferred to surrounding unburnt fuel and the atmosphere. Empirical models, on the other hand, rely upon a top-level model to determine the magnitude of heat exchanges. Simply put, empirical models are trying to describe the pattern (some elements of the processes), while the physical models are explicitly trying to capture the fundamental processes.

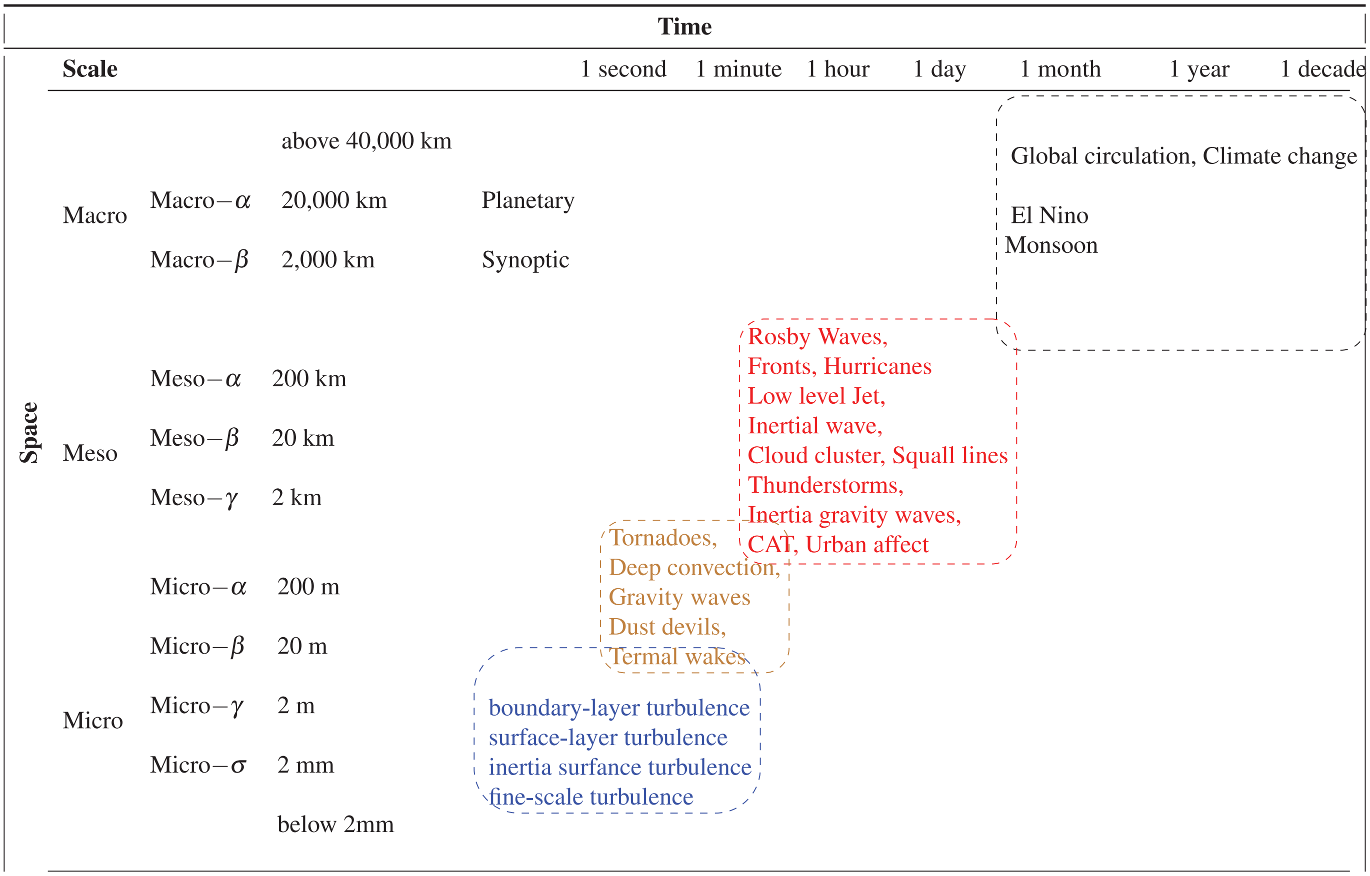
The empirical models depend on a simplified analytical rate of spread (ROS) to predict the propagation of a fire as a function of time (one or two dimensions in space and one dimension in time). These simplified mathematically based models (Rothermel 1972; Van Wagner (1987*a*, 1987*b*) had the advantage of solving fire propagation faster than real time for operational purposes. Physical fire models numerically solve equations for the fluid dynamics and thermochemistry of fires, e.g., FIRETEC (Linn et al. 2002) or WFDS (Mell et al. 2007). Accurate physical equations can be formulated but all require numerical solutions. Pastor et al. (2003) and Sullivan (2008) provided two comprehensive reviews on the earliest wildfire spread modeling.

The new generation of wildfire model used both physical and empirical fire models coupled to a numerical weather prediction (NWP) model or a computational fluid dynamics model (CFD). The coupled models included the interaction of wildfire with the surrounding atmosphere by means of changing the fire environment via humidity, temperature, and wind speed and direction. These models are four-dimensional models (three dimensions in space and one in time). Wildfire can impact the atmosphere directly via its heat and moisture fluxes or smoke. The approach of coupling atmosphere–fire feedbacks is applied by the following steps.

(1) Updating weather and fire variables simultaneously by running atmosphere and wildfire growth or combustion models in a parallel setting — Some atmospheric models are modified to have fire growth, fluxes, or emission solvers for parallel simulation. The computational time of these models is usually shorter as internal passing of data between two coupled models (input and output (I/O)) is faster than external communication.
(2) Integrating the fire's sensible heat flux, in terms of temperature, and latent heat flux (water vapor) to the atmosphere — The heat flux is exchanged by means of radiation in the lower surface of the atmospheric model and then via buoyancy, conduction, convection, and advection dynamics to the upper atmosphere. The extreme updraft and heat fluxes of a large fire can reach the tropopause in a few hours (often indicated by the appearance of pyrocumulus). A small domain simulation that is limited to the boundary layer or small box (as large as a few 1000 m in each dimension) cannot simulate a complete flux exchange.
(3) Updating the atmospheric composition and pollutants as the fire progresses — Wildfire aerosols and smoke block the solar insolation and change the heat budget. The blocking impact requires longer than a day's lead-time simulation.
(4) Updating weather and fire variables via evolution (two-way interaction) of scales of motion — The scale is another determining factor that differentiates the ability of a model to handle longer temporal simulations. As we explain in detail, all coupled models do not capture the full coupling steps.

Three-dimensional numerical atmospheric–wildfire models, including their physics, dynamics, and numerical methods, are distinguished by spatial and temporal scales of motion. The atmosphere is a continuing cascade of weather phenomena (Fig. 1)

Fig. 1. Scales of horizontal motion in the atmosphere (Bakhshaii and Johnson 2017; Stull 2017; Orlanski 1975).



ranging in characteristic size from millimetres to megametres in horizontal length and 10^{-4} to 10^{8} s in time. There are no simple sets of relationships that relate the state of the atmosphere at one instant of time to its state at another at all scales of motion. The models' physics and dynamics are strongly dependent on the scales of the target phenomena. This means that for different scales, there are often different sets of equations. Thus, to simulate a wildfire burning for a few days, we require, at the least, two parallel scales for the large-eddy scale (LES) and the mesoscale. The parallel simulation does not refer to parallel computation such as multi-processors here. Parallel simulations are two or more physical systems that integrate in time simultaneously, while the integration in serial simulations complete one after the other. There is a higher level of interaction between scales of motion in parallel simulations compared with serial simulations. Both parallel and serial simulations can be run by many or just one central processing unit (CPU) or graphical processing unit (GPU). The user-selected system of models for simulation can only present the phenomena that are resolved within the scale of the models. To save computational time, most operational fire models have not been coupled (or are only partially coupled) to the atmosphere or an atmospheric representative (CFD). Noncoupled fire models (e.g., FARSITE (Finney 1998), Prometheus (Tymstra et al. 2010), and BEHAVE (Andrews 2013)) simulate fire spread by using output from an atmospheric model and (or) weather observation, i.e., the fire does not alter the weather. The consequence is that the model output uncertainty of such noncoupled models will increase over a short period of time. Most semi-coupled models simulate the partial interaction or just within a limited scale of space and time (for more discussion, see the next section), e.g., FIRETEC (Linn et al. 2007) and WFDS (Mell et al. 2007).

Computationally feasible atmosphere–wildfire models can be constructed from either a fire spread model or computational reduced combustion models (quasi-physical models are very much of the former). WRF-FIRE, ARPS/DEVS-FIRE, and ForeFire/Meso-NH use a fully operational, multi-scale weather prediction model as a base and quasi-physical fire spread and combustion models as an added module for calculation of fire propagation, fluxes, and atmospheric variables. This paper describes the new generation of atmosphere–wildfire coupled models with their applications and features. Some of these models are summarized in Table 1. Before reviewing the above models' physics and numerical implementations, it is useful to briefly review the scale restraint and the numerical solution.

Scale does matter: some numerical terms

The earliest physical science models tend to deal with isolated microscale phenomena (e.g., wildfire spread model or the optical properties of ice crystals) so that their direct application is usually limited by the size and complexity of the surrounding environmental system (e.g., atmosphere). These physical models are usually solved analytically; however, the solutions of models are so complicated sometimes that we cannot perform the derivation or integration of a "prognostic" equation (which means that it involves time derivatives) analytically.

Environmental models in physical science are formulated according to basic physical principles such as conservation of mass, momentum, and thermodynamic energy. Many of these equations are prognostic. A model that contains prognostic equations is solved by time integration, and the prognostic variables of such a model must be assigned initial conditions. The integration often cannot be done analytically then; spatial discretization is required

Table 1. Atmosphere–fire models (2004–2017).

Coupled model	Coupling method	Spatial scale	Domain (m^2)	Time scale	CPU usage
FIRETEC	One way	1 mm–1 m	1 km^2	1 s–2 h	No real time
WFDS	One way	1 mm > 10 m	>2 km^2	1 s–4 h	No real time
CAWFE	Two ways	10 m–30 m	>10 km^2	1 s–hours	No real time
WRF-FIRE/SFIRE	Two ways	10 m–10 km	1 km–100 km	1 s–days	Real time
ForeFire/Meso-NH	Two ways	10 m–1 km	1 km–100 km	1 s–hours	~Real time
ARPS/DEVS-FIRE	Two ways	10 m–1 km	1 km–100 km	1 s–hours	No real time

prior to any numerical integration equations. Equations that do not contain time derivatives are called "diagnostic" equations. The diagnostic variables in a model can be computed from the prognostic variables and the external known variables.

The Navier–Stokes equations are used in the description of the atmosphere and wildfire. We are unable to obtain exact solutions to the Navier–Stokes equations as their variables change in time and space. As Charney (1951) explained, there is no simple set of relationships that relate the state of the atmosphere at one instant of time to its state at another. Physical approximations simplify the problem, for example, the Reynolds averaging along with closures[1] can be used to determine turbulent and convective fluxes. These approximate equations may describe the phenomena of interest more directly by removing phenomena of less interest (filtering) and then giving a set of equations that is more focused and appropriate for the phenomena of interest. For example, filtering sound waves results in faster integration in time (the anelastic approximation or low Mach approximation) or eliminating gravity waves (the quasi-geostrophic approximation) results in a more stable model for synoptic scale. Consequently, physical models (physical parameterization) are strongly dependent on and limited by the scale of phenomena because of their state equations, time integration, and approximations. The story of the first successful numerical weather prediction is the prime example of scale dependency and filtering process.

Bjerknes (1904) defined the problem of prognosis as the integration of the equations of motion of the atmosphere, and Richardson (1922) suggested the numerical solution for this problem. Richardson used a horizontal grid of about 200 km, and four vertical layers of approximately 200 hPa, centered over Germany. Using the observations at seven Universal Coordinate Times (UTC) on 20 May 1910, he computed the time derivative of the pressure in central Germany between 4 (7 − 3) and 10 (7 + 3) UTC. The prediction of pressure changes was 146 hPa, whereas there was no change in observation of the surface pressure. Today we know that the fast-moving gravity waves masked the initial rate of change of the meteorological signal because the initial conditions and integration were not balanced according to the scale of synoptic motion. These conditions are today well known as a violation of the Courant–Friedricks–Lewy theorem (Kalnay 2002). Later, Charney (1948, 1949) and Eliassen (1949) solved these problems by filtered equations of motion, slowly varying quasi-geostrophic equations, which filtered out gravity and sound waves, and predicted the pressure. We know today that the time step of integration should be smaller than the grid size (spatial distance) divided by the speed of the fastest traveling signal (in this case, horizontally moving sound waves, traveling at about 300 $m \cdot s^{-1}$). The filtered equation resolved the problem for faster integration. This can only be a correct assumption if we can justify and neglect the tendency of density in the continuity equation; then we can filter out sound waves. As we explained, this was a solution for the synoptic scale, while it cannot be justified at a small convection scale when the vertical acceleration is not negligible such as with thunderstorms or any cases in which the buoyancy force is a main factor.

All of these physical approximations, discretization, and numerical integrations introduce physical errors, which may or may not be considered acceptable for all applications of a model. After a suitable set of physical simplified equations has been considered, the choice of mathematical methods (i.e., finite difference, finite element, or spectral (Randall 2003)) to solve the system of equations introduces further numerical errors. We cannot eliminate the errors completely, but we can suppress certain kinds of errors. For example, in connection to the continuity (conservation of mass) equation, we can restrain any error in the conservation of global mass of dry air. This means that we can design our model so that the mass of dry air does not change as the atmosphere moves around the Earth; however, this correction does not apply in limited-area models of 200 km^2 domain or finer resolution. These sorts of models with mathematical parameterization in a particular scale of motion with some specific physical assumptions are limited by the scale. For this reason, multi-scale models have been developed for the atmosphere as a cascade of continuously connected multi-scale phenomena (Fig. 1).

Wildfire is a multi-scale event from the scale of an individual flame to that of a large fire plume. The complexity of wildfire involves interactions between the combustion processes and the surrounding atmosphere, terrain, and vegetation. To simulate all of the details of the coupled atmosphere–wildfire system over domains large enough to capture a large wildland fire's behavior requires significant parameterization and filtering to represent the combined essence of multi-scale physical phenomena. As a result, the simulation of wildfires requires a different approach from those employed in traditional combustion modeling (scales of centimetres and restricted to domain sizes on the order of 10 m). The physical parameterization of heat and moisture fluxes is developed in microscale. The physical parameterization demands a very fine resolution of terrestrial inputs such as land use, vegetation, and topography. The convection and pyrocumulus activity occurs at mesoscale, and the synoptic scale drives the main forcing such as wind and moisture. A common approach to include multi-scale phenomena requires multi-scale modeling to integrate all physical forces and interactions at the same time.

Next, we review the specific coupling (interaction) and numerical techniques within wildfire models as presented in the new generation of wildfire spread models.

FIRETEC

FIRETEC, developed at the Los Alamos National Laboratory, New Mexico, USA, is a simplification of the complex combustion reactions of a wildland fire using pyrolysis, char burning, hydrocarbon combustion, and soot combustion in the presence of oxygen (Linn 1997). The latest improvement to FIRETEC includes a further modified chemistry model (Linn et al. 2002). FIRETEC includes diffusivity of the heat transfers as the sum of three cascad-

[1]Closure is the process of approximation of subgrid-scale terms in Navier–Stokes equations. Subgrid-scale (SGS) terms are unknown flow quantities in a defined grid scale.

ing spatial large-eddy scales. While the original version of FIRETEC did not explicitly include the effects of radiation, the revised version included a simple radiant heat transfer model (Linn et al. 2002). As a result, fire propagation in zero wind or down slopes can be affected.

FIRETEC is a semi-coupled fire model as it does not fully interact with the larger scale (mesoscale) atmosphere. The fire physics is an ensemble average that is coupled to the atmosphere by HIGRAD (Reisner et al. 1998, 2000) at the scale of the fire model (microscale). HIGRAD is a CFD that adjusts the airflow to the terrain and topography rather than updating the boundary conditions (BCs). FIRETEC input is updated via HIGRAD. The feedback of fire does not pass to the entire atmosphere and is limited to the simulation of HIGRAD. The FIRETEC model does not use empirical relations to predict the spread and behavior of wildland fires. FIRETEC solves its system of equations using a finite volume numerical method. The model captures the physical process with some exceptions, e.g., convective heat transfer between solids and gases (Linn 1997; Linn and Harlow 1998; Linn et al. 2002). Structures smaller and larger than the resolved scale of the model, including individual flames or the fire plume, are not represented explicitly. FIRETEC dynamic uses the Boussinesq approximation that ignores the density variation in the atmosphere.

Overall, FIRETEC is a small eddy scale (the spatial integration is a fraction of 1 m) combustion simulation. Chemical heat release from the combustion process occurs only in computational grid cells that might be smaller than the flame length (Linn et al. 2002). Combustion is the result of the reaction rate of solid and gas phases using a Gaussian-shaped probability density function of temperature. The model is computationally expensive and limited to a small-eddy spatial and temporal scale. The lack of interaction to larger scales of atmospheric motion prohibits the application of the model for a simulation longer than a fraction of an hour or a domain larger than a kilometre.

Although FIRETEC is a wildfire model with limited scale and limited coupling capability, there are several detailed studies on the rate of fire spread propagation (Bova et al. 2015) and crown fire rate of spread (Hoffman et al. 2016) that have added value to wildfire modeling studies.

WFDS

The Wildland–urban interface Fire Dynamics Simulator (WFDS) is an extension of the Fire Dynamics Simulator (FDS) developed at the U.S. National Institute of Standards and Technology (NIST). This model is a fully three-dimensional, physics-based, semi-coupled fire–atmosphere model that uses approximations to the governing equations of fluid dynamics, combustion, and the thermal degradation of solid fuel (Mell et al. 2007). The significant difference between FIRETEC and WFDS is the physics of combustion. WFDS assumes that combustion occurs solely by mixing fuel gas and oxygen and is independent of temperature (FIRETEC conserves the potential temperature, while WFDS conserves enthalpy). The model assumes that the time scale of the chemical reactions is much shorter than the time scale of mixing, so the released energy associated with chemical reactions is not explicitly presented.

FDS is a large-eddy simulation (LES) model and its extension, WFDS, includes a low Mach number approximation to analytically eliminating acoustic wave propagation entirely from the dynamics. It also has a fast and direct pressure solver that results in a shorter computational time. To improve further computational efficiency, WFDS utilizes a multi-mesh to resolve the LES equations for a subgrid inner volume of 1.5 $km^2 \times 200$ m height with grid spacing as small as 1.6 m. The multi-mesh serves the model in the LES mode but it does not have the multi-nest features (McGrattan et al. 2013). This means that there is little advantage to overlaying meshes because information is only exchanged at the exterior boundaries. In other words, while the model can smoothly simulate the LES scale, the inner mesh feedback cannot update outside the boundary conditions and simultaneously adjust the coarse resolution values (there is no interaction between two overlay mesh cells). This can be a major limitation for simulation of a large wildfire, which is a multi-scale phenomenon.

The LES box model has an Eulerian framework (level set) to simulate the fire front. Comparison between the WFDS and FIRETEC (Lagrangian) fire spread models demonstrated similar results for crown fire spread within the range of a large empirical crown fire dataset (Hoffman et al. 2016). Although the evaluation of the two models provides some insights, these kinds of comparisons are limited due to the lack of detailed atmosphere and fuel data. The limitation of data impacts not only the initialization of any simulation, but also the evaluation of the process.

Overall, WFDS has the advantage over FIRETEC of being an open-source model. Both models are suitable for small fire studies for a short period of time as both are limited LES box models. WFDS is equipped with a limited version of data assimilation for nudging weather data. None of the above models has the capacity for wildfire forecasting (now-casting or short-term forecasting) at present.

CAWFE

The Coupled Atmosphere–Wildland Fire–Environment (CAWFE) model (Clark et al. 1996*a*, 1996*b*, 2004; Coen 2005) was developed at the National Center for Atmospheric Research (NCAR) as the first attempt to couple an atmospheric and fire model. First-generation CAWFE consists of the Clark–Hall mesoscale atmospheric model (Clark et al. 1996*a*, 1996*b*) coupled with a tracer-based fire spread model. The front-tracking scheme is called tracer (Clark et al. 2004) in CAWFE. Within each fuel cell, there are four moving points called tracers that represent the interface between burning and nonburning areas within the fuel grid cell. Fluxes such as sensible and latent heat on both the fuel and the atmospheric grids describe the location of tracers.

The three-dimensional CAWFE was based on the primitive equations of motion and thermodynamics that can represent the fine-scale dynamics (spanning millimetres to megametres in horizontal length) of convective processes and capture ambient meteorological conditions. Clark et al. (1996*a*, 1996*b*) revealed a dynamical explanation for fire-line breakup and geometry in a series of numerical simulations. The current version of CAWFE (Coen 2013) is composed of two parts, a numerical weather prediction model and a fire behavior module. The semi-physical fire module is fully coupled to the atmospheric model, while wildland fire processes occur at scales several orders of magnitude smaller than the atmospheric grid size (for example, 0.1 mm). Thus, CAWFE does not simulate flames, combustion chemistry, or consumption of oxygen. The fire module simulates the flaming front (Clark et al. 2004), rate of spread (Rothermel 1972), post-frontal heat release (Clark et al. 2004; Coen 2005), and sensible and latent heat fluxes for surface and crown fires (Coen 2013). The model has simulated small fires in LES mode to present at high resolution interaction of a small fire with eddies in the atmospheric boundary layer. To simulate the larger fire, CAWFE is equipped with a multi-nesting feature in which the nested grid refinement refines the grid spacing to the resolution of the finest resolution modeling domain in which fire growth is modeled. After the ignition time, the simulation ignites a fire in the finest domain and the model simulates the remaining period of interacting weather and fire behavior in all nests. CAWFE has the potential of mesoscale wildfire simulation; however, at its current stage, there is no report showing that it is fast enough for a real-time application.

WRF-FIRE

A numerical weather prediction (NWP) model offers an operational approach that also can be used in wildfire models. The NWP models are valuable for prediction or projection because of their scaled physics, dynamic parameterization, and data assimilation. It is logical to add wildfire to a fully operational weather model by simply adding a physics option in the Weather Research Forecast (WRF) model (Patton and Coen 2004; Mandel et al. 2011; Coen et al. 2013). WRF is an upgrade of the fifth-generation NCAR/Penn State Mesoscale Model (MM5) (Anthes and Warner 1978). The main benefits of using WRF are that it is an open-source model and is actively developed by a large community of scientists from all over the world (around 6000 registered users), leading to continuous improvements of the model. The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting the Advanced Research WRF (ARW) modeling system for use in a broad range of applications across scales ranging from 10s of metres to 10s of kilometres, including real-time forecast, research, coupled-model applications, regional climate research, and data assimilation. None of the previous models has been used as wildland fire real-time (when a simulation can perform faster than real time) forecast tools.

The separation of scientific codes from computation parallelization and other architectures made WRF a fast-growing community model. It supports multiple dynamics solvers and many physics modules. The WRF model consists of major programs, including the WRF Preprocessing System (WPS), WRF Data Assimilation (WRF-DA), and ARW or NMM dynamics solver. WPS is used primarily for (*i*) defining simulation domains, (*ii*) interpolating terrestrial data such as terrain, land use, and soil types, and (*iii*) converting, projecting, and interpolating meteorological data from another source such as global models to the WRF simulation domain. WRF-DA can be used to incorporate observations into the interpolated analyses created by WPS. It can also be used to update the WRF model's initial conditions as the WRF model runs in a cycling (updating in a fixed frequency) mode. ARW solver is the key component of the modeling system, which is composed of several initialization programs for simulations, and the numerical integration program (encompassing physics schemes and numeric and dynamics options). ARW solver is responsible for time integration of prognostic spatiotemporal discretized variables. It also updates the diagnostic variables along the internal and external forces for each grid point. ARW's forces include Coriolis, advection, buoyancy, mixing, and other physics (such as radiation, cloud, and fire). ARW solver handles the turbulence via several formulations for turbulent mixing and filtering. Some of these filters are meant to represent subgrid (smaller than 100s of metres) turbulence processes that cannot be resolved on the chosen grid. These filters remove energy from the solution and are formulated, in part, on turbulence theory and observations, or they represent energy sink terms in some approximation to the Euler equation. In large-scale models and most NWP models, vertical mixing is parameterized within the planetary boundary layer (PBL) physics. When a PBL parameterization is used, all other vertical mixing is disabled. The outline of turbulent mixing parameterizations and other numerical filters is available in the ARW technical note (Skamarock et al. 2005).

The modular structure is a tremendous advantage for adding new detailed physics. A land-surface module can use different developed schemes for microphysics of water vapor and hydrometeors (microphysics scheme), unresolved scale of convection (cumulus parameterization scheme), surface layer friction velocities and exchange coefficients (that enable the calculation of surface heat and moisture fluxes under surface layer scheme), and radiative forcing (radiation scheme). These schemes pass their estimated variables to a land-surface model (LSM). The LSM uses static information of the land's state variables and land-surface properties to calculate heat and moisture fluxes over land points and sea-ice points. These fluxes provide a lower boundary condition for the vertical transport done in the PBL schemes or the vertical diffusion scheme. The PBL is responsible for vertical subgrid-scale fluxes due to eddy transports in the whole atmospheric column, not just the boundary layer. Thus, when a PBL scheme is activated, explicit vertical diffusion is deactivated with the assumption that the PBL scheme will handle this process. The modular structure of WRF makes it possible to choose a different combination of scale-dependence physics or to add a completely new one such as wildfire spread physics.

The fire module is implemented as an added physics option in WRF. The module (physics package) is inspired by the CAWFE model. The fire–atmosphere coupling occurs through passing winds, temperature, and moisture from the lowest WRF level (the lowest level can be varying through different settings of vertical levels of the model) to the fire module. The fire module will use those winds to predict the fire spread and subsequent heat and water vapor emissions. Water vapor and heat emissions from the fire are passed back to WRF and distributed vertically through an assumed extinction depth (Patton and Coen 2004). WRF-FIRE (Mandel et al. 2011) calculates heat fluxes determined from an exponential decay function and distributes the sensible heat flux vertically to account for radiation. The WRF-FIRE module runs in LES (large-eddy simulation) mode, thus no PBL model is used. Turbulence was resolved by the grid and some subgrid-scale estimations for unresolved fluxes of momentum, heat, water vapor, and other diagnostics. Then, user-chosen WRF's land-surface models (LSM) would add the same quantities of heat and water vapor fluxes to the upper level of integration. Mandel et al. (2011) described the WRF-SFIRE version 3.3 (WRF 3.3). While any simulation depends on the domain's size and duration of simulation, WRF-FIRE executes its simulation faster than real time even with an inner nested domain as fine as decametres. Further improvement has been achieved by correction to near-surface winds (Coen et al. 2013). Coen (2013) found that the higher fuel loads increased the heat flux and fire-plume strength but had limited impact on spread rate. Kochanski et al. (2013*a*) introduced a simple fuel moisture model in SFIRE (SFIRE is the WRF's fire module that has been developed at the University of Colorado) that runs independently at each grid point. The fuel moisture model estimates the drying and wetting fuel equilibrium moisture content (Van Wagner and Pickett 1985; Viney 1991) with a time lag. They also coupled it with WRF-Chem to trace the fire emission as the fluxes of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and particulate matter (PM 2.5) were released into the atmosphere at the location of the fire. Mandel et al. (2014) presented an example of operational deployment in Israel, utilizing a fuel moisture data assimilation system based on the Remote Automated Weather Stations (RAWS) observations, allowing for fire simulations across landscapes and time scales of varying fuel moisture conditions. Peace (2014) investigated the interaction of the multi-scale three-dimensional atmospheric influence on bush fires in Australia via WRF-FIRE. The results showed that detailed information from mesoscale meteorology could not be neglected in forecasts of fire spread. Coen (2013) stated that the convective-scale NWP models such as CAWFE have an advantage over WRF in being designed to simulate weather in a complex terrain and with steep variable topography gradients. She also mentioned that WRF, a mesoscale model, aggressively dissipates fine-scale motions and gradients, distorting the evolving fire perimeter and strongly dampening the fire signature because steep gradients are smoothed as they attempt to form fire phenomena and build up to convective scales. While we could not find any references on structural design limitations of WRF, the statement emphasizes the importance of attention to the convection scale (meso-gamma) setting of WRF, which needs to be considered prior to any simulations.

ARPS/DEVS-FIRE

The Advanced Regional Prediction System (ARPS) was developed at the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (Xue et al. 2000, 2001). The ARPS utility is to serve as a tool for research and explicit prediction of convective storms and weather systems at the meso-gamma scales (Fig. 1). DEVS-FIRE (Ntaimo et al. 2004; Hu et al. 2012) is a raster-based fire spread model. The raster-based method treats the fire front as a series of grid-cell interactions rather than as the propagation of a contiguous front line. The DEVS-FIRE model treats weather as an external input. ARPS does not have fire spread, fluxes, or emission solvers for parallel simulation. The computational times of ARPS/DEVS-FIRE are longer as external passing of data between two coupled models (I/O) is slower than internal passing of data (Dahl et al. 2015). The coupled model of DEVS-FIRE and ARPS was developed in the same fashion as FIRETEC and HIGRADS coupling as defined earlier. ARPS was initially designed to simulate intense small-scale atmospheric convection, including the scales at which fire–atmosphere feedbacks become significant. Dynamic data assimilation methods also have been implemented, which improved DEVS-FIRE simulation results significantly (Xue et al. 2012*a*, 2012*b*).

ForeFire/Meso-NH

Meso-NH (Lafore et al. 1998) is an anelastic (filtered rapidly propagating acoustic oscillations) and nonhydrostatic mesoscale model intended to be applied to scales ranging from meso-gamma scale (1000 m) to microscale (10 m) simulations. It is the result of a collaboration between the Centre National de Recherche Météorologique and the Laboratoire d'Aérologie. The fire propagation model for the fire front is based on the Balbi formulation (Balbi et al. 2009). The Balbi model is a quasi-physical model that predicts the front propagation as a radiating panel in the direction normal to the front. The fire propagation solver ForeFire (Filippi et al. 2009; Balbi et al. 2009) uses a front tracking method that relies on a discretization in a Lagrangian manner. The burn probability and detection skill were calculated to compare the Rothermel and Balbi fire spread models (Filippi et al. 2014) for 80 fire cases. The burn probability is the frequency with which the model correctly predicts the burned area. The Rothermel model was slightly better for the burn probability skill score. The detection skill is the frequency with which a burned location was correctly simulated. Filippi et al. (2014) showed that the Balbi model had better performance on detection skill scores. The atmosphere's forcing from Meso-NH applies to ForeFire by a bi-linear interpolation in space and time and Meso-NH can treat imposed fire fluxes, i.e., heat and water vapor fluxes, at ground level. ForeFire/MesoNH (Filippi et al. 2011) uses fuel-dependent nominal values to estimate the heat fluxes and effective emitting temperature to treat radiation explicitly.

The ForeFire/Meso-NH model was evaluated using an experimental burn that took place on 23 February 2006 at Houston (Clements et al. 2007, 2008; Filippi et al. 2013). The simulation domain was designed to incorporate the dimensions of a fire flux experiment using a 1 km wide, 2 km long, 300 m high LES box with open boundary conditions, while the lateral flow boundary conditions were forced with the sounding (atmospheric profile 43 min before the fire start via radiosonde) data for the duration of the run (1–24 h). The model was run at two resolutions. Simulations at different resolutions showed that coupling effects were well reproduced even at low resolution (25 m, 5 m vertical) and results were quantitatively acceptable at a higher resolution (10 m, 3 m vertical) with amplitudes in temperature and vertical wind speed very close to those observed in the experiment. The fire flux experiment has already been used as a benchmark for forest fire simulation by WRF-SFIRE with a similar degree of agreement and similar resolutions (Kochanski et al. 2013*a*).

Discussion

The primary goal of wildland fire modeling is to create procedures that can be incorporated into calculation tools for both fire research and the day-to-day work of forest fire managers. The tools should indicate prior to the event the possible occurrence location and the progress and possible damages that a wildfire could cause, especially in the context of multiple simultaneous ignitions. The models ideally should run within an hour or so on 20 distinct fires under current computing capacity. For instance, Bakhshaii and Johnson (2018) found that the first day of the Horse River fire, 2016, Fort McMurray, Alberta, could be simulated in 6 h for five domains and the simulation used just 100 CPU and simulated four grid meso-scale domains 27 to 1 km and two LES domains of 250 and 10 m resolutions. Nonetheless, none of the current operational models can distinguish the few wildfires that will turn into large fires. The common problem in a fire season is the limitation of fire suppression teams and emergency responses. Any advancement of prior knowledge can improve the situation.

The evolution of wildfire spread models has been closely linked to the development of different wildfire methodologies and to advances in computer science and numerical weather prediction. Improvements in modelling, numerical methods, and remote sensing have been reflected in more powerful and versatile coupled systems, which have become more useful tools for wildfire management as demonstrated by Kochanski et al. (2013*b*) for the 2007 Santa Ana fires. Advances have been made due to increases in computing power, which now allow more complex simulations to be run. The applications and features of these tools are summarized in Table 1. The coupled models are different in applications as the computational, numerical, and some physical aspects of these models are designed for particular applications. Some of the coupled models such as WRF-FIRE (multi-scale and fully coupled in physics and computation platform) can simulate any large number of ignitions in 10 000 km^2 faster than real time (namely 3–6 h run for 24 h forecasts) with no combustion physics. Others can simulate the details of flame and combustion as small as a few metres in space such as FIRETEC but slower than real time. Some are open-source models where the modelling community has the ability to add, modify, and test new spread and combustion physics, while some are very limited to developer modifications. Models with a multi-scale coupling that can simulate fire and atmosphere fluxes and updraft above the tropopause can simulate pyrocumulus such as CAWFE, WRF-FIRE, ForeFire/Meso-NH, and ARPS/DEVS-FIRE. The performance of these tools varies as the result of the numerical processors, dependency on scale, and their computational platforms. Although the evaluations of models against the empirical data from past experimental burns provide some insights on the parameterizations and physics, these kinds of comparisons are limited due to the lack of detailed atmosphere and fuel data at the present. The limitation of data impacts not only the initialization of any simulation (new or old), but also the evaluation of the process. We have presented a comparison of the structure of models and their limitations based on their design rather than on performance.

The initial attempts to address the atmosphere feedback have improved the understanding of fire dynamics in research. CAWFE (Clark et al. 1996*a*, 1996*b*, 2004; Coen 2005) was one of the earliest attempts to simulate the atmosphere and fire feedback. FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2007) came with some more sophistication in the physics of fire. However, none of the above models could be used for operational real-time purposes for a variety of reasons, including being computationally demanding and their limited scale-resolving structure.

The choice of fire models depends on the questions to be answered, the availability of the models, and resources (e.g., data and computational resources). Questions related to chemical reactions, combustion, and flame at a horizontal scale of a few metres can be studied by FIRETEC for research purposes or WFDS can be used in the urban-interface fuel classes with its less complicated solver for a similar scale and with less computational demand. CAWFE and ForeFire/Meso-NH are very similar ideas. They are both large-eddy simulations (LES) that can perform fast enough for a near real-time application; however, LES models are only suitable for small domains and for a short period of time. The initial conditions of such models can add extra computational or financial costs. The public availability and compatibility to different platforms should be considered in advance.

WRF-FIRE (SFIRE) covers the synoptic scale, mesoscale, and microscale. WRF is a research and operational forecast model. The modular structure of WRF makes it a suitable platform to add more complexity to the system. It is also equipped with the WRF-DA, which can take advantage of existing and developing observations and satellite platforms. WRF-FIRE also calculates heat fluxes determined from an exponential decay function and distributes the sensible heat flux of each fuel type vertically to account for radiation (Mandel et al. 2011). ForeFire/Meso-NH (Filippi et al. 2011) uses fuel type to estimate the heat fluxes and effective emitting temperature to treat radiation explicitly.

The flame front propagation in CAWFE, ForeFire/Meso-NH, and WRF-FIRE has been treated as an expanding polygon with spread rates determined from a semi-physical function (Rothermel 1972). The level-set method in WRF-FIRE interpolated across multiple subgrid cells assesses the position of the fire front, as well as the burn time and fuel consumption at each cell within the burn area. The raster-based method treats the fire spread as a series of grid-cell interactions rather than the propagation of a contiguous front. ARPS/DEVS-FIRE uses the latter method. The grid-cell approach requires a smaller ratio between the ARPS and DEVS-FIRE grid resolutions.

Although the current ARPS/DEVS-FIRE and ForeFire/Meso-NH are able to capture the multi-scale of weather and fire, the framework is not sufficiently and computationally optimized to enable real-time runs comparable with WRF-FIRE. The main area of difficulty lies in the fact that these models (fire and atmosphere) currently run separately and exchange data externally and simultaneously. The external I/O on the High-Performance Computing (HPC) clusters does not determine proper wall-clock ratio (wall-clock time is the actual amount of time taken to perform a job). User time measures the amount of time that the CPU spends running the code, and the ratio of these cannot be determined when the model uses external I/O because the weather and fire models are not coupled in the same computer codes. The computational expense associated with the external I/O is too costly (slow) to be used for operational purposes. Separated weather and fire models would update one another continuously in a non-optimized computational state (Dahl et al. 2015).

Conclusion

This review focuses on the comparison of the new generation of atmosphere–fire models' capabilities and limitations rather than the performance evaluations of detailed physics or numerical schemes. This latter comparison requires empirical data that has been collected with evaluation criteria. There are several cited performance evaluation studies, but all came to a consensus that they lacked the required data to evaluate the physics of the models. We discussed the applications and limitations due to design of numerical schemes, resolved scale, or high-performance computational system.

The strategy of wildfire management has been to predict possible wildfire occurrence and behavior based on weather, chance, kind of ignition, fuel type, moisture content, topography, and rate of spread. Our current knowledge is insufficient for advance prediction and detection of high risk areas, measurement of the magnitude of heat output, or fire front size. The current approaches could be improved if we knew more of how wildfires ignited, spread, and were extinguished, and then we would be able to make better, faster, and more efficient decisions. Wildfire research and management are currently undergoing a significant evolution with coupled mechanistic fire and weather models as described in this review. The new developments and advancements in high-performance computing and satellite platforms give these new generations of wildfire–weather models enormous possibility for operational use. This evolution offers us two lessons. The first is that the skills that wildfire researchers and managers must bring to these advances are different than what were required 20 years ago. Second, our objectives in research and management will need to be adapted to define the complexity of the system and integrate the advances in environmental modeling.

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References

Albini, F. 1976. Estimating wildfire behavior and effects. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Gen. Tech. Rep. INT-30.

Anderson, H.E. 1969. Heat transfer and fire spread. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Res. Pap. INT-69.

Andrews, P.L. 2013. Current status and future needs of the BehavePlus Fire Modeling System. Int. J. Wildland Fire, **23**: 21–33. doi:10.1071/WF12167.

Anthes, R.A., and Warner, T.T. 1978. Development of hydrodynamic models suitable for air pollution and other mesometeorological studies. Mon. Weather Rev. **106**: 1045–1078. doi:10.1175/1520-0493(1978)106<1045:DOHMSF>2.0.CO;2.

Bakhshaii, A., and Johnson, E.A. 2017. Atmospheric observation under sampling problem: the impact of unresolved micro-scale boundary layer eddies on climate trends. Open J. Stat. **7**: 964–971. doi:10.4236/ojs.2017.76068.

Bakhshaii, A., and Johnson, E.A. 2018. Wildfire pyroconvection and CAPE: buoyancy's drying and atmospheric intensification [online]. *In* Experimental Fire/Smoke Forecasting, 2018 Joint WRF/MPAS Users' Workshop, Boulder, Colo., 12 June 2018. Available from http://www2.mmm.ucar.edu/wrf/users/workshops/WS2018/oral_presentations/4.5.pdf.

Balbi, J.-H., Morandini, F., Silvani, X., Filippi, J.B., and Rinieri, F. 2009. A physical model for wildland fires. Combust. Flame, **156**: 2217–2230. doi:10.1016/j.combustflame.2009.07.010.

Bjerknes, V. 1904. Das Problem der Wettervorhersage, betrachtet vom Standpunkt der Mechanik und der Physik. Meteorol. Z. **21**: 1–7.

Bova, A.S., Mell, W.E., and Hoffman, C.M. 2015. A comparison of level set and marker methods for the simulation of wildland fire front propagation. Int. J. Wildland Fire, **25**: 229–241. doi:10.1071/WF13178.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Gen. Tech. Rep. INT-16.

Byram, G.M. 1954. Atmospheric conditions related to blowup fires. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, N.C., Sta. Pap. SE-35.

Byram, G.M. 1959. Forest fire behavior. *In* Forest fires: control and use. *Edited by* K.P. Davis. McGraw-Hill, New York. pp. 90–123.

Charney, J.G. 1948. On the scale of atmospheric motions. Geofys. Publ. **17**: 1–17.

Charney, J.G. 1949. On a physical basis for numerical prediction of large-scale motions in the atmosphere. J. Meteorol. **6**: 372–385. doi:10.1175/1520-0469(1949)006<0372:OAPBFN>2.0.CO;2.

Charney, J.G. 1951. Dynamical forecasting by numerical process. *In* Compendium of meteorology. *Edited by* T.F. Malone. American Meteorological Society, Boston, Mass. pp. 470–482. doi:10.1007/978-1-940033-70-9_40.

Clark, T.L., Jenkins, M.A., Coen, J., and Packham, D. 1996*a*. A coupled atmosphere–fire model: convective feedback on fire-line dynamics. J. Appl. Meteorol. **35**: 875–901. doi:10.1175/1520-0450(1996)035<0875:ACAMCF>2.0.CO;2.

Clark, T.L., Jenkins, M.A., Coen, J., and Packham, D. 1996*b*. A coupled atmosphere–fire model: role of the convective Froude number and dynamic fingering at the fireline. Int. J. Wildland Fire, **6**: 177–190. doi:10.1071/WF9960177.

Clark, T.L., Coen, J., and Latham, D. 2004. Description of a coupled atmosphere–fire model. Int. J. Wildland Fire, **13**: 49–64. doi:10.1071/WF03043.

Clements, C.B., Zhong, S., Goodrick, S., Li, J., Potter, B.E., Bian, X., Heilman, W.E., Charney, J.J., Perna, R., Jang, M., Lee, D., Patel, M., Street, S., and Aumann, G. 2007. Observing the dynamics of wildland grass fires: FireFlux — a field validation experiment. Bull. Am. Meteorol. Soc. **88**(9): 1369–1382. doi:10.1175/BAMS-88-9-1369.

Clements, C.B., Zhong, S., Bian, X., Heilman, W.E., and Byun, D.W. 2008. First observations of turbulence generated by grass fires. J. Geophys. Res. **113**: D22102. doi:10.1029/2008JD010014.

Coen, J.L. 2005. Simulation of the Big Elk Fire using coupled atmosphere–fire modeling. Int. J. Wildland Fire, **14**: 49–59. doi:10.1071/WF04047.

Coen, J.L. 2013. Modeling wildland fires: a description of the Coupled Atmosphere–Wildland Fire Environment model (CAWFE). National Center for Atmospheric Research (NCAR), Tech. Note NCAR/TN-500+STR. doi:10.5065/D6K64G2G.

Coen, J.L., Cameron, M., Michalakes, J., Patton, E.G., Riggan, P.J., and Yedinak, K.M. 2013. WRF-Fire: coupled weather–wildland fire modeling with the Weather Research and Forecasting model. J. Appl. Meteorol. Climatol. **52**: 16–38. doi:10.1175/JAMC-D-12-023.1.

Dahl, N., Xue, H., Hu, X., and Xue, M. 2015. Coupled fire–atmosphere modeling of wildland fire spread using DEVS-FIRE and ARPS. Nat. Hazards, **77**: 1013–1035. doi:10.1007/s11069-015-1640-y.

Eliassen, A. 1949. The quasi-static equations of motion with pressure as independent variable. Geofys. Publ. **17**: 3.

Filippi, J.B., Bosseur, F., Pialat, X., Santoni, P.A., Strada, S., and Mari, C. 2011. Simulation of coupled fire/atmosphere interaction with the MesoNH-ForeFire models. J. Combust. **2011**: 540390. doi:10.1155/2011/540390.

Filippi, J.B., Pialat, X., and Clements, C.B. 2013. Assessment of ForeFire/Meso-NH for wildland fire/atmosphere coupled simulation of the FireFlux experiment. Proc. Combust. Inst. **34**(2): 2633–2640. doi:10.1016/j.proci.2012.07.022.

Filippi, J.B., Mallet, V., and Nader, B. 2014. Evaluation of forest fire models on a large observation database. Nat. Hazards Earth Syst. Sci. **14**: 3077–3091. doi:10.5194/nhess-14-3077-2014.

Finney, M.A. 1998. FARSITE: fire area simulator — model development and evaluation. USDA Forest Service, Rocky Mountain Research Station, Ogden, Utah, Res. Pap. RMRS-RP-4. doi:10.2737/RMRS-RP-4.

Hoffman, C.M., Canfield, J., Linn, R.R., Mell, W., Sieg, C.H., Pimont, F., and Ziegler, J. 2016. Evaluating crown fire rate of spread predictions from physics-based models. Fire Technol. **52**: 221–237. doi:10.1007/s10694-015-0500-3.

Hu, X., Sun, Y., and Ntaimo, L. 2012. DEVS-FIRE: design and application of formal discrete event wildfire spread and suppression models. Simulation, **88**(3): 259–279. doi:10.1177/0037549711414592.

Johnson, E.A., Miyanishi, K., and Weir, J.M.H. 1998. Wildfires in the western Canadian boreal forest: landscape patterns and ecosystem management. J. Veg. Sci. **9**(4): 603–610. doi:10.2307/3237276.

Kalnay, E. 2002. Atmospheric modeling, data assimilation and predictability. Cambridge University Press. doi:10.1017/CBO9780511802270.

Kochanski, A.K., Jenkins, M.A., Mandel, J., Beezley, J.D., Clements, C.B., and Krueger, S. 2013*a*. Evaluation of WRF-SFIRE performance with field observations from the FireFlux experiment. Geosci. Model. Dev. **6**: 1109–1126. doi:10.5194/gmd-6-1109-2013.

Kochanski, A.K., Jenkins, M.A., Mandel, J., Beezley, J.D., and Krueger, S.K. 2013*b*. Real time simulation of 2007 Santa Ana fires. For. Ecol. Manage. **294**: 136–149. doi:10.1016/j.foreco.2012.12.014.

Lafore, J.P., Stein, J., Asencio, N., Bougeault, P., Ducrocq, V., Duron, J., Fischer, C., Héreil, P., Mascart, P., Masson, V., Pinty, J.P., Redelsperger, J.L., Richard, E., and Vilà-Guerau de Arellano, J. 1998. The Meso-NH Atmospheric Simulation System. Part I: adiabatic formulation and control simulations. Ann. Geophys. **16**: 90–109. doi:10.1007/s00585-997-0090-6.

Lareau, N.P., and Clements, C.B. 2016. Environmental controls on pyrocumulus and pyrocumulonimbus initiation and development. Atmos. Chem. Phys. **16**: 4005–4022. doi:10.5194/acp-16-4005-2016.

Lareau, N.P., and Clements, C.B. 2017. The mean and turbulent properties of a wildfire convective plume. J. Appl. Meteorol. Climatol. **56**: 2289–2299. doi:10.1175/JAMC-D-16-0384.1.

Linn, R.R. 1997. A transport model for prediction of wildfire behaviour. Ph.D. thesis LA-13334-T, Los Alamos National Laboratory. Re-issue of Ph.D. thesis accepted by Department of Mechanical Engineering, New Mexico State University. doi:10.2172/505313.

Linn, R.R., and Harlow, F.H. 1998. Use of transport models for wildfire behaviour simulations. *In* Proceedings of the III International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology, Luso, Portugal, 16–20 November 1998. *Edited by* D.X. Viegas. Coimbra. pp. 363–372.

Linn, R., Reisner, J., Colman, J.J., and Winterkamp, J. 2002. Studying wildfire behavior using FIRETEC. Int. J. Wildland Fire, **11**(4): 233–246. doi:10.1071/WF02007.

Linn, R., Winterkamp, J., Edminster, C., Colman, J.J., and Smith, W.S. 2007. Coupled influences of topography and wind on wildland fire behaviour. Int. J. Wildland Fire, **16**: 183–195. doi:10.1071/WF06078.

Mandel, J., Beezley, J.D., and Kochanski, A.K. 2011. Coupled atmosphere–wildland fire modeling with WRF 3.3 and SFIRE 2011. Geosci. Model Dev. **4**: 591–610. doi:10.5194/gmd-4-591-2011.

Mandel, J., Kochanski, A.D., Vejmelka, M., and Beezley, J.D. 2014. Data assimilation of satellite fire detection in coupled atmosphere–fire simulation by WRF-SFIRE. *In* Advances in forest fire research. Imprensa da Universidade de Coimbra. doi:10.14195/978-989-26-0884-6_80.

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., and Overholt, K. 2013. Fire Dynamics Simulator, user's guide. 6th ed. National Institute of Standards and Technology, Gaithersburg, Md., and VTT Technical Research Centre of Finland, Espoo, Finland.

Mell, W., Jenkins, M.A., Gould, J., and Cheney, P. 2007. A physics-based approach to modeling grassland fires. Int. J. Wildland Fire, **16**: 1–22. doi:10.1071/WF06002.

Nelson, R.M., Jr. 2001. Water relations of forest fuels. *In* Forest fires: behavior and ecological effects. *Edited by* E.A. Johnson and K. Miyanishi. Academic Press, San Diego. pp. 79–149. doi:10.1016/B978-012386660-8/50006-4.

Ntaimo, L., Zeigler, B.P., Vasconcelos, M.J., and Khargharia, B. 2004. Forest fire spread and suppression in DEVS. Simulation, **80**(10): 479–500. doi:10.1177/0037549704050918.

Orlanski, I. 1975. A rational subdivision of scales for atmospheric processes. Bull. Am. Meteorol. Soc. **56**(5): 527–530. doi:10.1175/1520-0477-56.5.527.

Pastor, E., Zárate, L., Planas, E., and Arnaldos, J. 2003. Mathematical models and calculation systems for the study of wildland fire behaviour. Progr. Energy Combust. Sci. **29**(2): 139–153. doi:10.1016/S0360-1285(03)00017-0.

Patton, E.G., and Coen, J.L. 2004. WRF-Fire: a coupled atmosphere–fire module for WRF [online]. *In* The 5th WRF/14th MM5 Users' Workshop, Boulder, Colo. National Center for Atmospheric Research (NCAR). pp. 221–223.

Peace, M. 2014. Coupled fire–atmosphere simulations of three Australian fires where unusual fire behaviour occurred. Ph.D. thesis, School of Mathematical Sciences, University of Adelaide, Adelaide, Australia.

Pyne, S.J. 1984. Introduction to wildland fire: fire management in the United States. Wiley, New York.

Randall, D. 2003. An introduction to atmospheric modelling [online]. Department of Atmospheric Science, Colorado State University, Fort Collins, Colo. Available from http://kiwi.atmos.colostate.edu/group/dave/at604.html.

Reisner, J.M., Bossert, J., and Winterkamp, J. 1998. Numerical simulation of two wildfire events using a combined modeling system (HIGRAD/BEHAVE). *In* The Second Symposium on Forest and Fire Meteorology: AMS 78th Annual Meeting, Phoenix, Ariz., 11–16 January 1998. American Meteorological Society. pp. 6–13.

Reisner, J.M., Knoll, D.A., Mousseau, V.A., and Linn, R.R. 2000. New numerical approaches for coupled atmosphere–fire models. *Presented at* The Third Symposium on Fire and Forest Meteorology, Long Beach, Calif., 10 January 2000. American Meteorological Society.

Richardson, L.F. 1922. Weather prediction by numerical process. Cambridge University Press, Cambridge.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Res. Pap. INT-115.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W., and Powers, J.G. 2005. A description of the Advanced Research WRF version 2. National Center for Atmospheric Research (NCAR) Tech. Note TN-475+STR. doi:10.5065/D6DZ069T.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. **107**: 8149. doi:10.1029/2001JD000484.

Stull, R. 2017. Practical meteorology: an algebra-based survey of atmospheric science [online]. Available from https://www.eoas.ubc.ca/books/Practical_Meteorology/.

Sullivan, A.L. 2008. Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. Int. J. Wildland Fire, **18**: 349–368. doi:10.1071/WF06143.

Tymstra, C., Bryce, R.W., Wotton, B.M., Taylor, S.W., and Armitage, O.B. 2010. Development and structure of Prometheus: the Canadian Wildland Fire Growth Simulation Model. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta., Can. For. Serv. Inf. Rep. NOR-X-417.

Van Wagner, C.E. 1965. Describing forest fires — old ways and new. For. Chron. **41**(3): 301–305. doi:10.5558/tfc41301-3.

Van Wagner, C.E. 1967. Calculations on forest fire spread by flame radiation. Government of Canada, Department of Forestry and Rural Development, Petawawa Forest Experiment Station, Chalk River, Ont., Can. For. Branch Dept. Publ. No. 1185.

Van Wagner, C.E. 1987*a*. Forest fire research — hindsight and foresight. *In* Proceedings of the Symposium on Wildland Fire 2000, South Lake Tahoe, Calif., 27–30 April 1987. *Coordinated by* J.B. Davis and R.E. Martin. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., Gen. Tech. Rep. PSW-GTR-101. pp. 115–120.

Van Wagner, C.E. 1987*b*. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Ottawa, Ont., Can. For. Serv. For. Tech. Rep. 35.

Van Wagner, C.E., and Pickett, T.L. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Petawawa National Forestry Institute, Chalk River, Ont., Can. For. Serv. For. Tech. Rep. 33.

Viney, N.R. 1991. A review of fine fuel moisture modelling. Int. J. Wildland Fire, **1**: 215–234. doi:10.1071/WF9910215.

Xue, H., Gu, F., and Hu, X. 2012*a*. Data assimilation using sequential Monte Carlo methods in wildfire spread simulation. ACM Trans. Model Comput. Simul. (TOMACS), **22**(4): 1–25. doi:10.1145/2379810.2379816.

Xue, H., Hu, X., Dahl, N., and Xue, M. 2012*b*. Post-frontal combustion heat modeling in DEVS-FIRE for coupled atmosphere–fire simulation. Procedia Comput. Sci. **9**: 302–311. doi:10.1016/j.procs.2012.04.032.

Xue, M., Droegemeier, K.K., and Wong, V. 2000. The Advanced Regional Prediction System (ARPS) — a multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: model dynamics and verification. Meteorol. Atmos. Phys. **75**(3–4): 161–193. doi:10.1007/s007030070003.

Xue, M., Droegemeier, K.K., Wong, V., Shapiro, A., Brewster, K., Carr, F., Weber, D., Liu, Y., and Wang, D. 2001. The Advanced Regional Prediction System (ARPS) — a multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: model physics and applications. Meteorol. Atmos. Phys. **76**(3–4): 143–165. doi:10.1007/s007030170027.