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A review of a new generation of wildfire-atmosphere modeling

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Abstract

One of the first significant developments in wildfire modeling research was to introduce heat flux as wildfire line intensity (kW m^{-1}). This idea could be adapted to use 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 non- coupled models with a coupling mechanism. These models are tailored for specific spatial and temporal scales.

Keywords: Wildfire, Fuel, Fire behavior WRF-FIRE, FIRETEC, WFDS, CAWFE, ForeFire/Meso-NH, ARPS/DEVS-FIRE, Finite difference, Finite volume.

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) and in the 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

$$I = c \, dm/dt \quad (1)$$

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 dm/dt is the mass loss rate during flaming combustion. The formulation consists 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 2-dimensional geometry and statistical assumptions (Van Wagner, 1987a).

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 3-dimensional nature and vertical development of the phenomena (Van Wagner, 1987a). 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). Lareau and Clement (2016) found using a scanning Doppler lidar and mobile radiosonde system during two large wildfires in northern California that, compared to the ambient wind, the flow within the plume is characterized by much stronger velocities when outbound speeds exceeded 15 m/s and the wind profiles showed significant shear over the lowest 2 km of the atmosphere. Lareau and Clement 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 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., 2003). 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 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, b, 2004; Coen, 2005), Wildland Fire Module combined with the Weather Research and Forecasting numerical weather prediction system (WRF-Fire) (Patton et al., 2004; Mandel et al., 2011; Coen et al., 2013), ForeFire/Meso-NH (Filippi, 2011), and DEVS-FIRE/ARPS (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 were divided into two main approaches: empirical and physical. The most distinguishing attribute of a fully physical model of fire behavior in comparison to 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 (1-2 dimensions in space and 1 dimension in time). These simplified mathematically-based models (Rothermel, 1972; Van Wagner, 1987) 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 thermo-chemistry of fires, e.g. FIRETEC (Linn, 2002) or WFDS (Mell et al., 2007). Accurate physical equations can be formulated but all require numerical solutions. Pastor (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 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 4-dimensional models (3-dimensions in space and 1 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 (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 which 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-ways 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 model 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 (Figure 1) ranging in characteristic size from mm to Mm 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 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 to serial simulations. Both parallel and serial simulations can be run by many or just one CPU (Central Processing Unit) or GPU (Graphical Processing Unit). 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). Non-coupled fire models (e.g. FARSITE (Finney, 1998), Prometheus (Tymstra et al., 2010), BEHAVE (Andrews, 1986)) 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 non-coupled 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, 2007), WFDS (Mell et al., 2007).

Computationally feasible atmosphere-wildfire models can be constructed either from a fire spread model or computational reduced combustion models (quasi-physical models are very much of the former). WRF-FIRE, DEVS-FIRE/ARPS 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 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, sometimes the solutions of models are so complicated that we cannot perform the derivation or integration of a *prognostic* equation (means 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 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 its 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 closures¹ that 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

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.

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 7 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 violation of the Courant–Friedricks–Lewy theorem (Kalnay, 2003). 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/s). 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

222 sound waves. As we explained, this was a solution for the synoptic scale while it cannot be
223 justified at a small convection scale when the vertical acceleration is not negligible, such as
224 with thunderstorms or any cases in which the buoyancy force is a main factor.

225 All of these physical approximations, discretization and numerical integrations
226 introduce physical errors, which may or may not be considered acceptable for all applications
227 of a model. After a suitable set of physical simplified equations has been considered, the
228 choice of mathematical methods (i.e. finite-difference, finite element or spectral (Randal,
229 2004)) to solve the system of equations introduces further numerical errors. We cannot
230 eliminate the errors completely, but we can suppress certain kinds of errors. For example, in
231 connection to the continuity (conservation of mass) equation, we can restrain any error in the
232 conservation of global mass of dry air. This means that we can design our model so that the
233 mass of dry air does not change as the atmosphere moves around the earth. However, this
234 correction does not apply in limited area models of 200 km² domain or finer resolution.
235 These sorts of models with mathematical parameterization in a particular scale of motion
236 with some specific physical assumptions are limited by the scale. For this reason, multi-scale
237 models have been developed for the atmosphere as a cascade of continuously connected
238 multi-scale phenomena (Figure 1).

239 Wildfire is a multiscale event from the scale of an individual flame to a large fire
240 plume. The complexity of wildfire involves interactions between the combustion processes,
241 the surrounding atmosphere, terrain and vegetation. To simulate all the details of the coupled
242 atmosphere –wildfire system over domains large enough to capture a large wildland fire's
243 behavior requires significant parameterization and filtering in order to represent the
244 combined essence of multi-scale physical phenomena. As a result, the simulation of wildfires
245 requires a different approach from those employed in traditional combustion modeling

(scales of centimeters and restricted to domain sizes on the order of ten meters). The physical parameterization of heat and moisture fluxes is developed in micro-scale. 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 multiscale phenomena requires multiscale 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 Los Alamos National Laboratory, 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 cascading 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 which is coupled to the atmosphere by HIGRAD (Reisner et al., 1998, 2000) at the scale of the fire model (micro-scale). 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, 1998a; Linn et al., 2002a). 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 km.

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., 2015) that have added value to wildfire modeling studies.

WFDS

The Wildland-Urban interface Fire Dynamics Simulator (WFDS) is an extension of Fire Dynamics Simulator (FDS) developed at the US National Institute of Standards and Technology (NIST). This model is fully 3D, physics-based, semi-coupled fire-atmosphere, and uses approximations to the governing equations of fluid dynamics, combustion, and the

thermal degradation of solid fuel (Mell, 2007). The significant difference between FIRETEC and WFDS is the physics of combustion. WFDS assumes 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 sub-grid inner volume of 1.5 km² by 200 m height with grid spacing as small as 1.6 m. The multi mesh serves the model in the LES mode while the multi mesh does not have the multi nest features (McGrattan et al., 2013). This means 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 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., 2015). 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 open source. 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 (nowcasting or short-term forecasting) at present.

CAWFE

The Coupled Atmosphere–Wildland Fire–Environment (CAWFE) model (Clark et al., 1996a, 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., 1996a, 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 non-burning 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 mm to Mm in horizontal length) of convective processes and capture ambient meteorological conditions. Clark (1996a, 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 fire (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 that shows 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 et al., 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 open source and actively developed by a large community of scientists 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 meters to 10s of kilometers, including: real-time forecast, research, coupled-model applications, regional climate research and data assimilation. None of the previous models have 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: 1) defining simulation domains; 2) interpolating terrestrial data such as terrain, land use, and soil types; and 3) 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, numeric and dynamics options). ARW solver is responsible for time integration of prognostic spatial-temporal 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 sub-grid (smaller than 100s of meters) 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., 2008).

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), un-resolved 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 sub-grid 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 de-activated with the assumption that the PBL scheme will handle this process. The modular structure of WRF made 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

419 and water vapor emissions. Water vapor and heat emissions from the fire are passed back to
420 WRF and distributed vertically through an assumed extinction depth (Patton et al., 2004).
421 WRF-FIRE (Mandel et al., 2011) calculates heat fluxes determined from an exponential
422 decay function and distributes the sensible heat flux vertically to account for radiation. The
423 WRF fire module runs in LES (large eddy simulation) mode, thus no PBL model is used.
424 Turbulence was resolved by the grid and some sub-grid scale estimations for unresolved
425 fluxes of momentum, heat, water vapor, and other diagnostics. Then, user chosen WRF's
426 land-surface models (LSM) would add the same quantities of heat and water vapor fluxes to
427 the upper level of integration. Mandel et al. (2011) described the WRF-SFire version 3.3
428 (WRF 3.3). While any simulation depends on the domain's size and duration of simulation,
429 WRF-Fire executes its simulation faster than real time even with an inner nested domain as
430 fine as decameters. Further improvement has been achieved by correction to near-surface
431 winds (Coen et al., 2012). Coen (2012) found that the higher fuel loads increased the heat
432 flux and fire-plume strength but had limited impact on spread rate. Kochanski et al. (2012)
433 introduced a simple fuel moisture model in SFIRE (SFIRE is the WRF's fire module that has
434 been developed at the University of Colorado) that runs independently at each grid point. The
435 fuel moisture model estimates the drying and wetting fuel equilibrium moisture content (Van
436 Wagner and Pickett, 1985; Viney, 1991) with a time lag. They also coupled it with WRF-
437 Chem to trace the fire emission as the fluxes of carbon dioxide (CO₂), carbon monoxide
438 (CO), methane (CH₄) and particulate matter (PM 2.5) were released into the atmosphere at
439 the location of the fire. Mandel et al. (2014) presented an example of operational deployment
440 in Israel, utilizing a fuel-moisture-data-assimilation system based on the Remote Automated
441 Weather Stations (RAWS) observations, allowing for fire simulations across landscapes and
442 time scales of varying fuel-moisture conditions. Peace (2014) investigated the interaction of
443 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 (2018) 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 couldn't 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 (figure 1). DEVS-FIRE (Ntamo 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 (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., 2012a, b).

ForeFire/Meso-NH

Meso-NH (Lafore, 1999) is an anelastic (filtered rapidly-propagating acoustic oscillations) and non-hydrostatic mesoscale model, intended to be applied to scales ranging from meso-gamma scale (1000 m) to micro-scale (10 m) simulations. It is the result of a collaboration between the Centre National de Recherche Météorologique and Laboratoire d'Aérodynamique. 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. MesoNH/ForeFire (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 hours). 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).

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 MacMurray, Alberta, could be simulated in 6 hours for 5 domains and the simulation used just 100 CPU and simulated 4 grid meso-scale domains 27 to 1 km and 2 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.

517 The evolution of wildfire spread models has been closely linked to the development
518 of different wildfire methodologies and to advances in computer science and Numerical
519 Weather Prediction. Improvements in modelling, numerical methods, and remote sensing
520 have been reflected in more powerful and versatile coupled systems, which have become
521 more useful tools for wildfire management as demonstrated by Kochanski (2013) for the
522 2007 Santa Ana fires. Advances have been made due to increases in computing power, which
523 now allow more complex simulations to be run. The applications and features of these tools
524 are summarized in table 1. The coupled models are different in applications as the
525 computational, numerical and some physical aspects of these models are designed for
526 particular applications. Some of the coupled models, such as WRF-Fire (multiscale and fully
527 coupled in physics and computation platform), can simulate any large number of ignitions in
528 10000 km² faster than real time (namely 3-6 hours run for 24 hours forecasts) with no
529 combustion physics. Others can simulate the details of flame and combustion as small as a
530 few meters in space such as FIRETEC but slower than real time. Some are open source
531 models where the modelling community has the ability to add, modify and test new spread
532 and combustion physics while some are very limited to developer modifications. Models
533 with a multiscale coupling that can simulate fire and atmosphere fluxes and updraft above the
534 tropopause can simulate pyrocumulus such as CAWFE, WRF-Fire, ForeFire/Meso-NH, and
535 DEVS-FIRE/ARPS. The performance of these tools varies as the result of the numerical
536 processors, dependency on scale and their computational platforms. Although the
537 evaluations of models against the empirical data from past experimental burns provide some
538 insights on the parameterizations and physics, these kinds of comparisons are limited due to
539 the lack of detailed atmosphere and fuel data at the present. The limitation of data not only
540 impacts on 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 a performance comparison.

The initial attempts to address the atmosphere feedback have improved the understanding of fire dynamics in research. CAWFE (Clark et al., 1996 a, b, 2004; Coen, 2005) was one of the earliest attempts to simulate the atmosphere and fire feedback. FIRETEC (Linn et al., 2002) and Wildfire Dynamic Simulator (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 meters 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, meso and micro scales. 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).

MesoNH/ForeFire (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, MesoNH/ForeFire 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 sub-grid 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 Meso-NH/Fore-Fire 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 to 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 the CPU spends running the code and the ratio of these cannot be determined when the model uses external input and output 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 paper 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 wildfire possible occurrence and behavior based on weather, chance and kind of ignition, fuel type and 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 advancement 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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Table and Figure captions

Table 1. Atmosphere-Fire models (2004-2017)

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

Table 1. Atmosphere-Fire models (2004-2017)

Coupled-model	Coupling-method	Spatial scales	Domain (m²)	Time scales	CPU usage
<i>FIRETEC</i>	One way	1mm –1m	1 km ²	1 s – 2 h	No real time
<i>WFDS</i>	One way	1mm >10m	>2 km ²	1 s – 4 h	No real time
<i>CAWFE</i>	Two ways	10 m- 30 m	>10 km ²	1 s – hours	No real time
<i>WRF-FIRE/SFIRE</i>	Two ways	10 m- 10km	1km- 100km	1 s – Days	Real time
<i>Meso-NH-ForeFire</i>	Two ways	10 m- 1km	1km- 100km	1s- hours	~ Real time
<i>ARPS/DEVS-FIRE</i>	Two ways	10 m- 1km	1km- 100km	1s- hours	No Real time

Draft

Time