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Procedia Computer Science 9 (2012) 302 – 311

Procedia Computer Science

International Conference on Computational Science, ICCS 2012

Post-frontal combustion heat modeling in DEVS-FIRE for coupled atmosphere-fire simulation

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Abstract

Modeling the heat released from a burning wildfire is essential to support coupled atmosphere-fire simulation. This paper presents post-frontal combustion heat modeling in the wildfire spread model of DEVS-FIRE. The developed heat model integrates features from both the BURNUP model and the heat model of WRF-Fire to compute the heat flux of wildfire. To model fuel consumption, it uses the BURNUP model to calculate the burning time and employs an exponentially decreasing fuel mass loss curve to derive the fuel consumption rate. Experiment results are presented and compared with those from the heat model of WRF-Fire. Using the developed heat model, a coupled atmosphere-fire simulation based on DEVS-FIRE and the ARPS atmospheric model is run to demonstrate the impact of the mutual interaction between wildfire and weather on wildfire spread.

Keywords: wildfire; coupled atomosphere-fire simulation; heat model, DEVS-FIRE, ARPS

1. Introduction

Simulation of wildfire spread plays important roles in wildfire management. Reliable modeling of wildfire spread requires not only an accurate portrayal of the fuels and topography at ground level, but also an accurate representation of the manner in which the fire and the atmosphere above it affect one another. In an effort to achieve more accurate simulations of wildfire spread, a two-way coupling between the discrete event wildfire spread model DEVS-FIRE [1, 2] and the Advanced Regional Prediction System atmospheric model (ARPS) [3, 4] is currently being developed to capture the fire-atmosphere feedbacks. To support coupled atmosphere-fire simulation, the DEVS-FIRE model needs to be extended to compute the heat release of post-frontal combustion of the wildfire.

A post-frontal combustion heat model is essential for coupled atmosphere-fire simulation because the heat flux of a wildfire constantly affects weather conditions, which in turn continuously influences the fire spread behavior. Wildfire is a complex process combined by procedures of energy releasing in chemical reactions and the transport of that energy [5]. As a consequence, all the factors associated with those chemical or physical procedures in turn have a strong influence on fire growth. Weather conditions as one of the factors are also significantly affected by the heat flux released from a fire. Therefore, in order to predict the spread of a wildfire, one needs to calculate the heat flux and thus requires accurate heat models.

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doi:10.1016/j.procs.2012.04.032

In most three-dimensional physics-based fire propagation models, like FIRETEC [6] or ForeFire [7], heat formulation is an inherent part of the fire spread computation. However, for empirical-based fire spread models such as DEVS-FIRE that use Rothermel's fire behavior model [8], a separated heat release model needs to be developed. In Rothermel's model, reaction intensity is calculated when computing the fire spread rate. Given the heat content of a certain fuel, the heat flux can be technically calculated from the reaction rate, but this reaction rate is only valid on the fire fronts and thus cannot be used to calculate the heat release for post-frontal combustion. For post-frontal combustion, Albini and Reinhardt in [9] propose a more accurate model that is usually referred to as BURNUP, where fire is assumed to sublime fuels, and heat is transferred into fuels by both convection and radiation. In this way, BURNUP simulates the fuel combustion process from which heat production of a wildfire can be derived. This model is adopted by FARSITE to calculate smoke and heat output for post-frontal fire behavior [10]. Clark, Coen et al. in [11] simplify BURNUP's mass loss curves as exponentially decreasing curves, and use only one parameter (referred to as the "weighting factor") to be determined by experiment data. As a result, each type of fuel has a weighting factor expressing the rate of mass loss, and with this rate the heat flux is modeled as a function of fuel mass loss in a given period. In our work, we inherit Clark's method to calculate the heat flux when the mass loss is known, but instead of using an invariable mass loss curve for a given type of fuel we employ a method similar to BURNUP to model the mass loss curve. The resulting heat flux model is more realistic in the sense that it incorporates environmental factors such as wind speed and fire intensity.

The coupled atmosphere-fire simulation in our work is based on the DEVS-FIRE model and the ARPS model. DEVS-FIRE, built on Discrete Event System Specification (DEVS) formalism [12], is a two-dimensional wildfire spread and suppression simulation model. DEVS-FIRE models a wildfire area as a cellular space containing individual cells, and they are coupled together according to the Moore neighborhood. Each cell is approximated to have uniform fuel, terrain, weather and fire behavior; Rothermel's model [8] is implemented on each of the cells for calculating the maximum fire spread direction and rate, and an elliptical expanding curve is then employed to calculate when to send ignition signals to neighboring cells. Fire spread simulation in DEVS-FIRE is partially validated in [13] by comparing simulation results with those from FARSITE [14]. Besides fire spread simulation, DEVS-FIRE also supports fire suppression simulation with realistic firefighting tactics. More details on this aspect can be found in [15].

ARPS is a nonhydrostatic three-dimensional model system developed by the Center for Analysis and Prediction of Storms; while the primary motivation is storm-scale modeling, the model contains a wide variety of formulations/parameterizations that suit it for weather modeling over a wide range of scale. The model equations are integrated over a staggered Arakawa C-grid mapped on a curvilinear, terrain-following coordinate system to account for orographic effects. The system also includes self-contained routines for data assimilation and preprocessing, as well as software for plotting and viewing the simulation results. The scale flexibility of ARPS is well-suited to the demands of simulating atmospheric response to the complex regions of intense surface heat flux found in wildfires. Previous research, e.g. [16], indicates that this response is highly dependent on the large-scale atmospheric conditions ranging from the surface to several kilometers above ground level. Thus, an accurate prediction of wildfire spread spanning several hours must reliably capture the temporal evolution of these conditions as well as the small-scale phenomena generated near the fire. ARPS can accomplish this by capturing the large-scale conditions in a relatively inexpensive coarse-grid simulation and then using the results to provide initial and boundary conditions for a high-resolution simulation containing the region of fire spread.

Coupled atmosphere-fire simulation has been researched in several previous works. Clark, Coen et al. in [11] coupled a nonhydrostatic numerical mesoscale atmosphere model with a BURNUP based fire spread model. Mandel, Beezley et al. in [17] developed WRF-Fire, which improved upon Clark's work by replacing the atmosphere model with WRF (Weather Research and Forecasting Model) due to the legacy code of Clark's model is serial and "not supported, and difficult to modify or use for real cases requiring real meteorological data, topography, and fuel maps". WRF also uses a level-set-based method instead of the tracer-based method in its fire model to enhance flexibility. Coupled atmosphere-fire simulations were also developed using physical-based fire models. Examples include HIGRAD/FIRETEC [18] and MesoNH-ForeFire [19].

2. The heat model in DEVS-FIRE

The developed heat model in DEVS-FIRE is built on several existing models in literature. Thus before presenting the heat model in DEVS-FIRE, we describe those models on which our work is based.

2.1. Reaction rate in Rothermel's model

DEVS-FIRE employs Rothermel's model to calculate the rate of fire spread. Although the model of reaction intensity exists in Rothermel's model, it cannot be used to calculate heat flux for DEVS-FIRE. In Rothermel's model, before the calculation of fire spread rate, the reaction intensity is first calculated as:

$$I_R = \Gamma\, w_n\, h\, n_M\, n_s, \tag{1}$$

where Γ is the optimum reaction velocity, w_n is the net fuel load, h is the fuel particle low heat content, n_M is the moisture damping coefficient and n_s is the mineral damping coefficient. Assuming all the heat is released into atmosphere, one can use I_R as the heat flux. However, fuel load quickly decreases with time, so this reaction rate is only valid in the beginning period of a fire. Also, this rate is independent of many important factors such as weather conditions. For those reasons, as an empirical model, although Rothermel's model relatively precisely models the rate of fire spread, the intermediate reaction intensity is invalid when calculating heat released from a fire.

2.2. Burning rate in BURNUP

BURNUP is an empirical burning rate model where the assumption for heat transfer is that the fuel consumption process is similar to a sublimation process. With this assumption, BURNUP has an excellent feature that a fuel element "will burn at a rate that depends upon the environment in which it is placed" [20]. As a result, many environmental factors become the inputs of BURNUP (like summarized in [21]), including fire intensity, wind speed and air temperature.

Although sublimation is not the real burning process, by applying parameter determination, this model can still produce a comparatively precise burning rate. The fuel diameter reduction rate in BURNUP is:

$$\frac{dD}{dt} = \frac{h_{eff}\left((T_F - T_C)/(T_F' - T_C')\right)(\rho_o'/\rho_0)}{a' + b'M}, \tag{2}$$

where D is the fuel diameter, h_{eff} is the heat transfer coefficient, T_F is the temperature of fire, T_F' is the temperature of fire in BURNUP experiments (928K), T_C is the sublimation temperature, T_C' is the sublimation temperature in BURNUP experiment (673K), ρ_o is the oven dry fuel mass density, ρ_o' is the oven dry fuel mass density in BURNUP experiments (466 kg m^{-3}), M is the fuel moisture fraction, a' and b' are the coefficients determined by experiments. Wind speeds contribute to this reduction rate via h_{eff} that consists of a convective heat transfer coefficient and a radioactive heat transfer coefficient, and wind speeds are used to determine the convective heat transfer coefficient. Moreover, the fuel diameter function is models as:

$$D(t) = D(0)(1 - t/\tau_c), \tag{3}$$

where $D(t)$ is the fuel diameter at time t (assuming the fuel is ignited at time 0), τ_c is the burning time (at which, the fuel burns down to 0), and $D(0)$ is the initial fuel diameter. From these assumptions, the fractional mass remaining can be derived as:

$$F(t) = \frac{m(t)}{m(0)} = (1 - t/\tau_c)^2, \tag{4}$$

$$\tau_c = \frac{T_F' - T_C'}{T_F - T_C} \frac{\rho_0}{\rho_o'} \frac{D(0)}{h_{eff}} (a' + b'M), \quad (5)$$

where $m(t)$ is the fuel mass at time t, and $m(0)$ is the initial fuel mass.

In this model, the fuel mass loss curve (the curve of fractional fuel mass remaining) is consistent with experiment results after $a'$and b' are decided, and the curve is a decreasing quadratic curve. Moreover, this burning rate is reasonably affected by many factors like fire temperature, fuel moisture, fuel mass density and wind speed, although the importance of wind could be underestimated as described on page 175 in [20].

2.3. Heat flux in WRF-Fire

Clark, Coen et al. simplify the mass loss curve in BURNUP to an exponentially decreasing function with only one coefficient *W* (named *weighting factor*) [11]. For each fuel type, a weighting factor is specified by the same empirical method as in BURNUP. Then the weighting factor of a fuel represents its fuel mass loss curve; for example, *W* is 7 for tall grass and *W* is 180 for chaparral. This model is adopted by WRF-Fire [17]. Since our heat model is closely related to that of WRF-Fire, below we present the heat model in WRF-Fire. In section 3, we also compare the results of the two models. According to the model in WRF-Fire, the fractional fuel mass remaining is then modeled as:

$$F(t) = exp(-t/T_f), \quad (6)$$

$$T_f = \frac{W}{0.8514}, \quad (7)$$

where T_f is the number of seconds for the fuel to burn down to $1/e \approx 0.3689$ of the original quantity. After that, each weighting factor decides the fuel mass loss curve of a type of fuel. Heat flux is then modeled as:

$$\phi_h = \frac{(F(t) - F(t+\Delta t))w_l h}{\Delta t(1+M_f)}, \quad (8)$$

where w_l is the fuel load, h is the heat content, and M_f is the fuel particle moisture content. The weakness of this model is that the heat flux is not influenced by wind speed, fire temperature and some other important factors. Also, this model implies that a fuel will burn down to a quantity that is close to zero since the mass loss curve is exponentially decreasing, and it is contradicted by the findings of [21] indicating that woody fuel consumption is variable from 9.1% to 89.9%.

2.4. Heat model of DEVS-FIRE

To retain the simplicity and to model the partial fuel consumption, the same as in WRF-Fire, we model the fractional fuel mass remaining as an exponentially decreasing function before the burning time in BURNUP is arrived at. Moreover, after that burning time is reached, we model the fuel to stop losing weight, and use a parameter (C) to specify the final fraction as $exp(-t/C)$. The resulting fuel mass loss fraction is shown as in equations (9).

$$F(t) = \begin{cases} exp\left(-\frac{t}{C\tau_c}\right), & t \le \tau_c \\ exp\left(-\frac{1}{C}\right), & t > \tau_c \end{cases} \qquad where\ \tau_c = \frac{928-673}{T_F - T_C} \frac{\rho_0}{446} \frac{D(0)}{h_{eff}} (a' + b'M). \quad (9)$$

Furthermore, considering that the fuel load, moisture, and heat content are specifically modeled in Rothermel's model, we employ those to calculate the heat flux:

$$\phi_h = \frac{(F(t)-F(t+\Delta t))w_n\, h\, n_M\, n_s}{\Delta t}, \quad (10)$$

where w_n is the net fuel load, h is the fuel particle low heat content, n_M is the moisture damping coefficient, and n_s is the mineral damping coefficient.

As can be seen, the major difference between this model and the heat model in WRF-Fire is the different mass loss curves and the different resulting fuel mass remaining fractions. In the heat model of WRF-Fire, the mass loss curve for a burning fuel is determined by a single weighting factor, whereas in our proposed heat model it depends on many characteristics of the fuel and the environment around the fire. In WRF-Fire, a fuel is finally all consumed, whereas in our model a certain fuel fraction more practically remains when a fire is self-extinguished.

With our proposed heat model, the combustion history can be more realistically simulated. However, for each type of fuel, instead of a single weighting factor, two parameters (a' and b') as shown in equation (5) have to be determined using the empirical method in [9], which increases the difficulty of applying this model.

2.5. Heat Release Computation in DEVS-FIRE

In DEVFIRE, the heat flux of a wildfire is calculated by an atomic DEVS model coupled with the fire spread model. At any time, when the state of a cell in the fire spread model switches from "unburned" to "burning", a message including the current time and the reference of this cell is sent to the heat model. The heat model records the information it receives and remains passive if there is no message except in the updating time points, which are the time points for DEVS-FIRE to output heat flux for each of the ignited cells.

In an updating time point, equation (10) is applied to calculate the heat flux. For each of the cell received, the burning time at the beginning of the last simulation step is calculated as:

$$t = max(ignition\ time\ point, last\ updating\ time\ point) - ignition\ time\ point.$$

The increment of the burning time at the end of the last simulation step is calculated as:

$$\Delta t = current\ updating\ time\ point - max(ignition\ time\ point, last\ updating\ time\ point).$$

Other inputs of equation (10) (such as fuel moisture fraction or heat content) are read in from the cell reference. The reason that DEVS-FIRE directly applies equation (10) to calculate the heat flux is the assumption (introduced in section 1) that each cell is considered to have a uniform fire behavior; thus, the burning area of a cell is always the entire area of that cell after it is ignited.

3. Experiments

3.1. Mass loss curve comparison and heat flux comparison

Fuel mass loss curve is not affected by environmental factors in WRF-Fire, and our proposed model tries to solve this problem. We propose to use the burning time calculated from BURNUP as shown in equation (5) to draw the fuel mass loss curve; at the same time, WRF-Fire obtains the curve by a constant weighing factor and the resulting constant T_f as shown in equation (6). In order to compare the difference, we set C in equation (9) to 1. The burning time (τ_c) in our model (as shown in equation (9)) then plays the same role as T_f in the heat model of WRF-Fire (as shown in equation (6)). We first performed experiment to illustrate that with changing fuel moisture or wind speed, T_f in WRF-Fire remains the same, but τ_c in our proposed model largely varies.

We set the fuel type to hard wood litter, the initial fuel diameter to 0.3 m, the fuel mass density to 400 kg m^{-3}, the fire temperature to 1350 K, the fuel moisture fraction to 0, and change the wind speed from 0 m s^{-1} to 50 m s^{-1}. In WRF-Fire, after knowing the fuel type is hard wood litter, T_f is then 1057 seconds. As shown in Fig. 1(a), although wind speed significantly changes, T_f remains the same since it is only decided by the fuel type; meanwhile, in our model, τ_c decreases when wind speed becomes larger. The total reduction of τ_c is about 20% when the wind speed

grows from 0 m s^{-1} to 50 m s^{-1}. It is then more consistent with the observation in real fires that the larger the wind speed, the faster the fuel will lose mass.

On the other hand, when setting wind speed to 20 m s^{-1}, leaving other parameters the same as above, and changing only the fuel moisture fraction, as shown in Fig. 1(b), T_f still remains the same in the heat model of WRF-Fire while τ_c greatly increases with the growth of fuel moisture. When the fuel moisture fraction is 0.5, τ_c is about 2.5 times as large as when the fuel moisture fraction is 0. With our proposed model, like in most of fires, wet fuels lose mass slower than dry fuels.

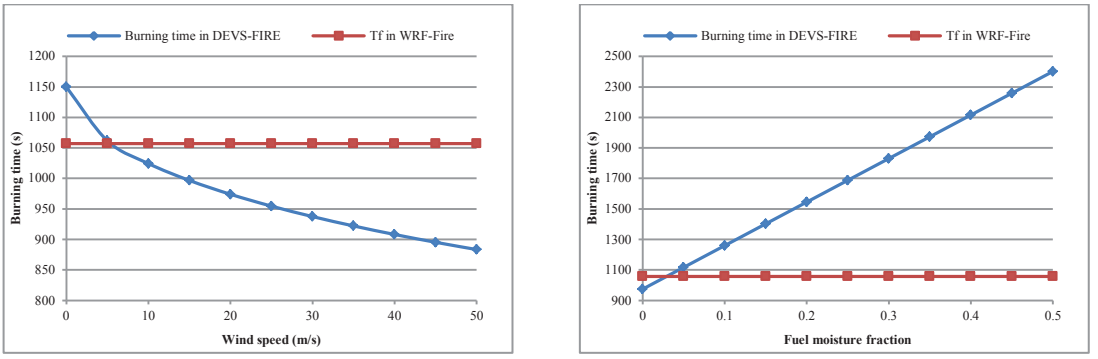

Fig. 1. (a) Comparison of burning time (τ_c) in DEVS-FIRE and T_f in WRF-Fire in changing wind speed; (b) Comparison of burning time in DEVS-FIRE and T_f in WRF-Fire in changing fuel moisture fraction.

With this calculation of τ_c we then draw the mass loss curves of our proposed DEVS-FIRE heat model when wind speed is 0 m s^{-1}, 30 m s^{-1} and 50 m s^{-1} (as shown in Fig. 2(a)), and when fuel moisture is 0, 0.3 and 0.5 (as shown in Fig.2(b)). They are compared with the corresponding mass loss curve of WRF-Fire. It is clearly seen that the curve of WRF-Fire remains the same, and in our proposed model the curve changes when wind speed or fuel moisture changes. Moreover, in our proposed DEVS-FIRE heat model, fuel stop to lose mass when τ_c is reached. This heat model in turn may provide more precise heat flux calculations for DEVS-FIRE.

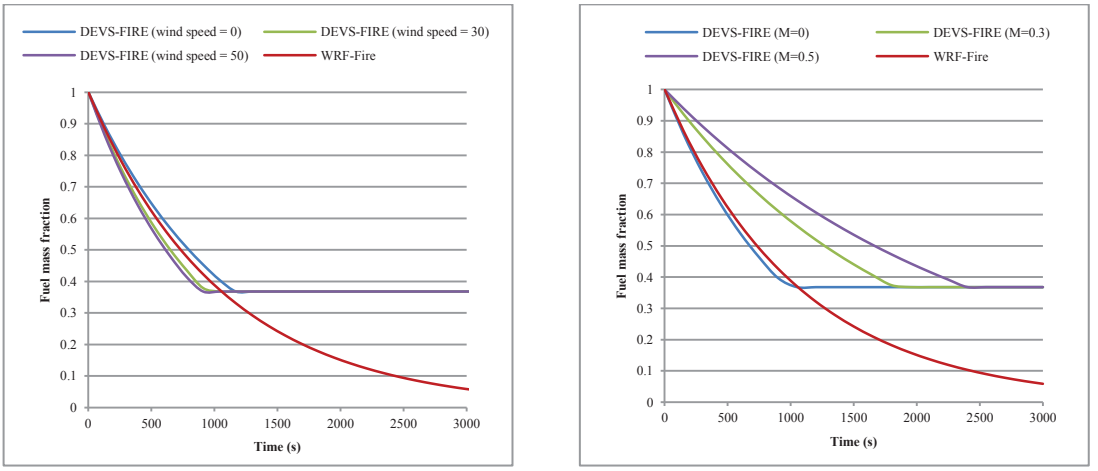

Fig. 2. (a) Fuel mass loss curves of WRF-Fire and DEVS-FIRE with different wind speed; (b) Fuel mass loss curves of WRF-Fire and DEVS-FIRE with different fuel moisture fraction.

We performed another experiment to compare the heat flux produced by WRF-Fire and DEVS-FIRE, where we set wind speed to 20 m s^{-1} and used two fuel moisture fractions, 0 and 0.5. For heat flux calculations, we set the heat content and fuel load as those of hardwood litter fuel, i.e. heat content is 18606.7 kJ kg^{-1} and fuel load is 0.7 kg m^{-2}.

Also, we set mineral content to 0, and net fuel load is then equivalent to fuel load. Also, the moisture content of extinction was set to 0.7. All the other parameters were held the same as in previous experiments.

Four groups of heat flux data were compared: DEVS-FIRE heat flux for a fuel moisture fraction of 0; DEVS-FIRE heat flux for a fuel moisture fraction of 0.5; WRF-Fire heat flux for a fuel moisture fraction of 0; and WRF-Fire heat flux for a fuel moisture fraction of 0.5. It should be noted that although the fuel moisture fraction does not affect the fuel mass loss curve in WRF-Fire, it still influences the heat flux since it is an input of WRF-Fire's heat flux model as shown in equation (8).

The results are displayed in Fig. 3. When the fuel moisture fraction is 0, the two models have similar heat flux before the DEVS-FIRE burning time (974 seconds) is reached. In DEVS-FIRE, heat flux is influenced by wind speed, so it is different from the one of WRF-Fire. After reaching the burning time, DEVS-FIRE outputs the heat generated in the last simulation step and stops to output heat flux; meanwhile, WRF-Fire continues to output an exponentially decreasing heat flux. When the fuel moisture fraction is 0.5, both DEVS-FIRE and WRF-Fire output less heat flux than when the fuel moisture fraction is 0. However, the change of heat flux in DEVS-FIRE is more remarkable. In DEVS-FIRE, the initial heat flux reduced to about 17% of the initial heat flux when the fuel moisture fraction is 0, whereas WRF-Fire's initial heat flux reduces to about 67%. The reason is that in DEVS-FIRE, increased fuel moisture largely slow down the consumption of fuel. Again, once the burning time (2401 seconds in this case) is reached, DEVS-FIRE stops to output the heat flux.

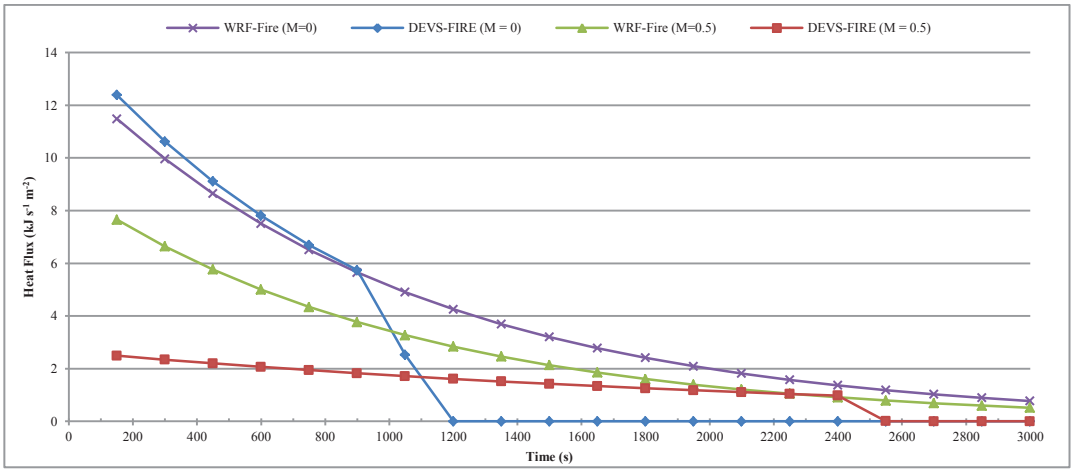

Fig. 3. Heat flux comparison between DEVS-FIRE and WRF-Fire when fuel moisture fraction is 0 and 0.5.

3.2. DEVS-FIRE/ARPS coupled simulation

The current method of coupling DEVS-FIRE to ARPS involves inserting the spatial distribution of the surface sensible heat flux calculated by the heat model proposed for DEVS-FIRE into ARPS and, in turn, inserting the near-surface weather conditions (temperature, humidity, wind speed, and wind direction) calculated by ARPS into DEVS-FIRE at regular time intervals. DEVS-FIRE is able to run at a higher grid resolution than ARPS without much additional cost; furthermore, the ARPS grid needs to be larger than the DEVS-FIRE grid in order to avoid the fire spreading to the lateral boundaries and conflicting sharply with the boundary conditions. Therefore, the grids are never identical for both models, and this information exchange requires some method of inexpensive grid mapping and data interpolation.

Currently, the ARPS and DEVS-FIRE grids are matched geographically using the latitude/longitude coordinates of the southeastern-most DEVS-FIRE grid cell as a reference. ARPS is generally run at coarser resolution, so the heat flux data from all DEVS-FIRE cells within 0.5d (where d is the horizontal grid spacing in ARPS) of a given

ARPS grid point are mapped onto that grid point using a simple average. Meanwhile, weather data at DEVS-FIRE cell locations between ARPS grid points are obtained via biquadratic interpolation (used in hopes of maintaining some of the data structure near sharp gradients/boundaries) and written to an ASCII file for DEVS-FIRE to read. (It should be noted here that the heat flux inserted into ARPS is entirely confined to the first layer above the surface, instead of being distributed vertically as in other models such as WRF-Fire. This is done in hopes of better capturing the intense heat flux convergence immediately above the combustion zone; however, this method has produced numerical instability in some ARPS simulations involving very intense fires and may thus require modification for future case studies.)

To demonstrate the importance of coupling the weather model to the fire model, a pair of 2-hour simulations were run using an idealized atmosphere with weak static stability and initially-uniform, vertically-sheared zonal wind over a uniform fuel bed. DEVS-FIRE was run at 10-meter resolution while ARPS was run at 30-meter resolution, which required a 0.1-second time step for the ARPS integration. For the uncoupled simulation, ARPS was allowed to respond to the heat generated by DEVS-FIRE, but DEVS-FIRE was not allowed to respond to changing weather conditions calculated by ARPS; for the coupled simulation, both models ran in parallel and exchanged information at 30-second intervals.

Even though the burn intensity at the fire front is the same for both simulations, coupling the models (instead of having ARPS respond to DEVS-FIRE but not vice versa) has a clear impact on the atmospheric response. This is illustrated in Fig. 4, which compares the near-surface atmospheric potential temperature perturbation and wind in the vicinity of the northern half of the fireline for the uncoupled (top) and coupled (bottom) simulations at t = 5280 seconds. In the uncoupled simulation a succession of strong, nearly-stationary vortices forms in the south-central portion of the plot; this is not observed in the coupled simulation.

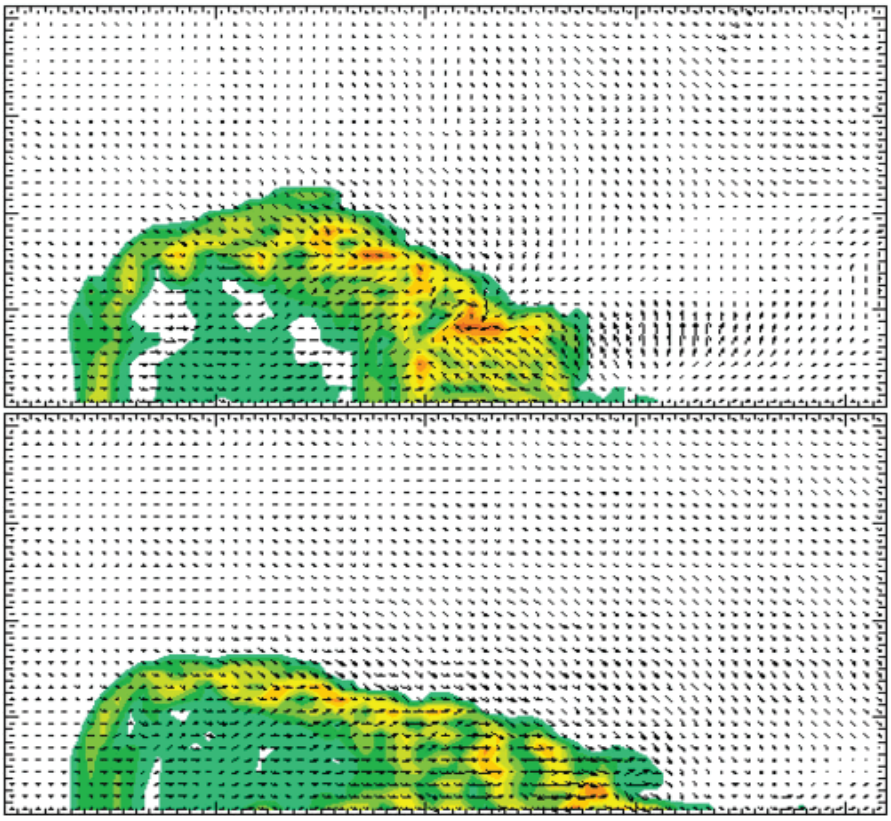

Fig. 4. Simulated atmospheric response at 6 meters AGL for uncoupled (top) and coupled (bottom) DEVS-FIRE/ARPS model runs at t = 5280 seconds. Arrows represent horizontal wind vectors, while color fills show positive potential perturbations (relative to the idealized horizontally homogeneous base state) in 5°C increments ranging from <= 0 (white) to 40°C (dark orange).

The cause of these vortices is apparent in Fig. 5, which shows the fire spread progressions calculated by DEVS-FIRE; in the uncoupled simulation, the fireline develops sharp corners or kinks on either side of the line of symmetry. When the atmospheric adjustment is not factored into the spread rate calculations, these kinks persist for the entire simulation and provide a constant focus for vertical vorticity generation in the atmosphere immediately above; in a coupled simulation, such a vortex on the north side of the line of symmetry would increase the spread rate north of the kink while decreasing it south of the kink. This would "smooth out" the fireline in time, which would in turn reduce the tendency for additional vortices to form in these areas while current atmospheric and fuel conditions persisted.

On the other hand, the coupled simulation also shows enhanced vorticity generation and spread rate on the flanks of the initial fireline, as evidenced by the bulges in the second and third panels in the bottom row of Fig. 5. The wind changes responsible for these bulges stem from the horizontal vorticity generated by intense buoyancy gradients at the fireline; this vorticity is increasingly tilted and stretched as the fireline bulges advance beneath it, which in turn amplifies the bulges until they merge at the line of symmetry. Thus, atmosphere-fire coupling is subject to both positive and negative feedbacks, and the coupled simulation reveals the impacts of both simultaneously (decreasing fire spread to the north and south but increasing it to the east). Such feedbacks are difficult, if not impossible, to evaluate qualitatively in advance and have been shown in previous studies (e.g. [11]) to exert a large cumulative effect on both the fire spread and the atmosphere near wildfires lasting several hours or more. To confirm and validate the impact of these effects within the DEVS-FIRE/ARPS coupled model, additional simulations seeking to recreate fire spread from an actual wildfire case lasting several days are currently underway.

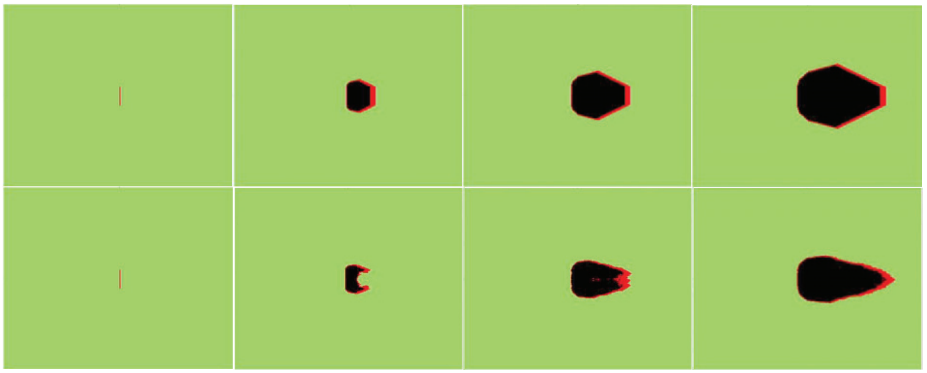

Fig. 5. Simulated fire spread from uncoupled (top) and coupled (bottom) DEVS-FIRE/ARPS model runs at (from left to right) t = 30, 1800, 3600, and 5400 seconds. Grid cells are plotted as unburned (green), ignited/burning (red), and burned out (black).

4. Conclusion

This paper presents post-frontal combustion heat modeling for the DEVS-FIRE wildfire spread model. The developed heat model integrates features from both the BURNUP model and the heat model of WRF-Fire. To model fuel consumption, it uses the BURNUP model to calculate the burning time and employs an exponentially decreasing fuel mass loss curve to derive the fuel consumption rate. With this heat model, a DEVS-FIRE/ARPS coupled atmosphere-fire simulation using uniform fuel model and flat terrain was performed which demonstrates the impact of the coupled simulation on wildfire spread.

Future work includes running more simulations to evaluate the developed models and to simulate wildfire spread for historical wildfires. In the process, the heat transfer computations used in ARPS will be modified to mitigate the risk of numerical instability, e.g. by distributing the heat flux over a specified atmospheric depth and/or refining the parameterizations used to estimate radiative flux through the air near the surface. Furthermore, it should be noted that the current simulations are slower than real-time, even when using more than a hundred processors working in parallel; for example, the coupled 2-hour simulations presented here required from 6 to 8 hours to produce, largely

because of the small time step required for integrating the atmospheric governing equations in ARPS at high spatial resolution to avoid immediate instability. Therefore, current efforts also focus on further parallelizing and streamlining ARPS computations (e.g. optimizing grid resolution and time step) as well as improving the efficiency of the information exchange between ARPS and DEVS-FIRE.

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