New Features in WRF-SFIRE and the Wildfire Forecasting and Danger System in Israel

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Abstract

This paper describes new developments in WRF-SFIRE and related software in the past two years: interfaces to GIS, fireline intensity and fire danger assessment, ignition in a coupled atmosphere-fire model from an observed fire perimeter, fuel moisture model and assimilation of RAWS fuel moisture data, rendering of smoke transport and coupling with atmospheric chemistry and aerosol schemes by WRF-Chem, and an operational deployment.

1 Introduction

Wildland fire is a complicated multiscale process. The fire behavior is affected by very small-scale processes occurring at the flames (pyrolysis, combustion). Slightly larger-scale turbulent processes induce mixing of the combustible gasses with the ambient air, and transport of heat, moisture and combustion products into the atmosphere affecting the fire as well. In a case of a wildland fire all these processes, no matter how small-scale, are affected to some degree by larger scale weather conditions since the energy from larger scales drives a cascade of gradually smaller and smaller eddies. Synoptic flows interact with topography and land use characteristics generate local winds that drive wildland fire propagation. Large-scale weather patterns induce changes in temperature and humidity that affect fuel moisture, thus affecting the fire behavior as well. If a fully physical representation of the wildland fire propagation were chosen, all this range of scales would have to be modeled. Although this approach is technically feasible to some degree for very small fires (Linn and Cunningham, 2005; Mell et al., 2007), the massive computational costs of such simulations make them prohibitive from the operational point of view. Also, capturing within one model the small-scale combustion processes and large scale weather conditions including clouds, winds and precipitation is practically impossible. Fortunately, coupling of a mesoscale weather model with a simple 2D fire spread model allows to capture a practically important range of wildland fire behavior.

Wildland fires are closely coupled with the atmosphere. Winds drive the fire propagation. Conversely, the fire influences the weather through the heat and vapor fluxes from burning hy-
drocarbons and evaporation. The buoyancy created by the heat from the fire can cause intense updrafts inducing very strong surface winds, which in turn affect the fire. The fire-induced updrafts may also generate pyro-cumulus and fire storms. Therefore, a large fire may significantly affect the local atmospheric conditions creating “its own weather.” The atmosphere interacts also with the fuel properties. Periods of warm and hot weather decrease fuel moisture increasing the fire hazard, and making fires more intense. Conversely, local precipitations or nocturnal moisture recovery tend to decrease fuel combustibility and inhibit fire spread. Coupling a weather model with a simple fire spread model and a simple fuel moisture model allows to capture these interactions, without explicit resolving of the small scale combustion and water adsorption processes, in a computationally modest way.

WRF-SFIRE (Mandel et al., 2009, 2011a) combines the Weather Research and Forecasting Model (WRF) (Skamarock et al., 2008), with the fire spread (SFIRE) implemented by the level-set method. WRF-SFIRE is a two-way coupled fire-atmosphere model, so the heat fluxes from fire component provide forcing to the atmosphere, which influences winds, which in turn modify the fire spread. Similar models include MesoNH-ForeFire (Filippi et al., 2011). Recently, the model was expanded with fuel moisture model, and chemical transport of emissions (Fig. 1). The model is able to run faster than real time on several hundred cores, with the fire model resolution of few meters and horizontal atmospheric resolution on the order of 100m, for a large real fire (Jordanov et al., 2012). However, the operational deployment discussed in Sec. 8 uses coarser meshes on a smaller number of processors.

WRF-SFIRE has evolved from CAWFE (Clark et al., 2004; Coen, 2005). The code currently supports the semi-empirical fire spread model (Rothermel, 1972), inherited from the CAWFE code. Support of alternative fire spread models (Balbi et al., 2009; Fendell and Wolff, 2001) is in progress. The current code and documentation are available from OpenWFM.org. A version from 2010 is distributed with the WRF release as WRF-Fire (Coen et al., 2012; OpenWFM, 2012).

Validation studies of WRF-SFIRE are now available for a large-scale wildfire (Kochanski et al., 2013c) as well as for a microscale simulation of a grass burn experiment (Kochanski et al., 2013d). The coupling of the fire heat release with the atmosphere allows a detailed study
of the effect of wind shear on fire propagation (Kochanski et al., 2013a). Examples of work from other groups using WRF-SFIRE include Simpson et al. (2013) and Peace et al. (2011).

This paper consolidates for the first time in a journal form new developments in the SFIRE software system in the two years since the reference paper Mandel et al. (2011a), scattered in extended abstracts and conference proceedings, and complements them by new results: interfaces to GIS (Sec. 2), new fireline intensity and fire danger assessment tools (Sec. 3), ignition in the coupled atmosphere-fire model from a developed fire perimeter (Sec. 4), fuel moisture model (Sec. 6), assimilation of RAWS fuel moisture data (Sec. 7), and an operational deployment (Sec. 8). We do not describe the basic principles and operation of the core of WRF-SFIRE here, and refer to Mandel et al. (2011a) and the User’s Guide (OpenWFM, 2013) instead.

2 Data management and visualization

WRF-SFIRE input is integrated with the standard WRF inputs, prepared by the WRF Preprocessing System (WPS) and the real.exe utility in WRF. In addition to meteorological data needed for WRF, SFIRE requires high-resolution topography and fuel maps. These are typically available in Geotiff format.

Geotiff is a standard for georeferencing metadata in Tagged Image File Format (TIFF) files (Ritter and Ruth, 2000). The geotiff format is particularly useful for fire related data and fine-scale topography, because it allows a compact representation of data on large meshes with thousand of cells (pixels) in each dimension. Geotiff support has been added to WRF-SFIRE in two forms (Beezley et al., 2011). The utility convert_geotiff creates geogrid files, which can be read by any standard installation of WPS. It has command line flags to control various geogrid attributes such as the size of the tiles, and it creates a header that contains both a description of the tiles and the geocoding (projection and reference points). TopoGrabber (http://laps.noaa.gov/topograber) is a Python application based on this work that is capable of downloading and converting topographical data automatically. The modified geogrid code, available with SFIRE distribution from http://openwfm.org, works in a similar way. Here the geotiff library is wrapped around an abstraction layer that reads the data in tiles. The main ad-
vantage is that it can read floating point data directly rather than convert to and from fixed point as required by the geogrid file format, and it can handle large meshes more easily.

WRF output are files in NetCDF format, which needs to input into suitable graphics program. Visualizations paths to various packages are provided, including VAPOR and KML format for Google Maps and Google Earth (Beezley et al., 2012). What has caught the most attention is the wrf2kmz script at https://github.com/jbeezley/wrf2kmz. This utility converts the NetCDF files from WRF-SFIRE into KML and the compressed variant KMZ. It uses the matplotlib Python package to generate pseudo color images of the data in wrf output files. It then uses another python library called simplekml to construct the KMZ file. The script can be modified to customize the style. This is the software used to generate the Google Maps and Google Earth images in this paper and in our previous work referenced here, and behind a prototype web interface (Beezley et al., 2012) as well as the operational system, described in Sec. 8.

3 New fireline intensity and fire danger mapping

This section is based on the extended abstract (Mandel et al., 2011b). Byram’s fireline intensity (Byram, 1959) is the heat produced per unit length of the fireline in unit time (J/m/s) in the so-called flaming zone behind the fireline. Hence, it is given by

\[ I = HRw \quad (1) \]

where \( H \) (J/kg) is the heat contents of the fuel, \( R \) (m/s) is the spread rate, and \( w \) (kg/m\(^2\)) is the fuel amount that burns in the flaming zone. In practice, the fuel amount burned \( w \) is estimated as a fixed fraction of the fuel load \( w_0 \) (kg/m\(^2\)), typically 0.9.

Though Byram’s fireline intensity is routinely used for practical guidance, it does not depend on the speed of burning. However, if the fuel burns slowly, much of the burning takes place at a distance from the fireline and it may not contribute much to the severity of the fire, while a fast burning fuel will release its heat close to the fireline.

A new concept of fireline intensity was introduced (Mandel et al., 2011b) as the amount \( J \) of heat generated by the advancing fireline from the newly burning fuel only, in a small unit of
time. Assume that the fuel fraction after ignition decreases exponentially with the time \( t \) from ignition, as \( e^{-\tau/T_f} \), where \( T_f \) is the fuel burn time, i.e., the time when \( 1 - e^{-1} \approx 63\% \) of fuel has burned. Then,

\[
J = \frac{HRw_0}{2T_f} \text{ (J/m/s)}.
\] (2)

Unlike Byram’s fireline intensity (1), the new fireline intensity, given by (2), takes into account the effect that a faster burning fuel will create a more intense heat concentrated at the fireline. The reason why the time unit is squared is that over a longer time, the fireline advances longer distance, and the amount of fuel it will process will also burn longer.

To estimate the simulated fire severity, the code computes the fireline intensities and the reaction intensity (which is the same as the released heat flux intensity, \( J/s/m^2 \)). The fireline intensities are computed from the fire rate of spread \( R \). Since \( R \) is well-defined on the fireline only, the fireline intensities are defined on mesh nodes next to the fireline only as well.

Separate computations are made as a component of a fire danger rating to estimate the severity of a potential fire. These quantities are computed from the maximal rate of spread at any location taking the wind speed and the slope at that location, and they can be used to plot potential fire severity maps. This is a concept similar to FLAMMAP, which computes various potential fire characteristics (Finney, 2006).

4 Initialization from a fire perimeter

The fire model starts the fire from a given ignition point at a given time. Instead, we want to start the model from a given fire perimeter at a given time (from now on, called the perimeter time). However, the fuel balance and the state of the atmosphere depend on the history of the fire, which is not known. We create an approximate artificial history of the fire based on the given fire perimeter and the perimeter time, the fuel map, and the state of the atmosphere during the period before the perimeter time. The history is encoded as the time of ignition, given at every node in the domain, also known in the literature as the fire arrival time. We then run the
fire-atmosphere model as usual, except we use the prescribed ignition time instead of the spread model until the perimeter time. By replaying the artificial fire history, we burn the fuel and release the heat into the atmosphere gradually, and hopefully allow a proper fuel balance and an atmospheric circulation to develop, corresponding to the given fire perimeter. At the perimeter time, the complete coupled atmosphere-fire model takes over.

In Kondratenko et al. (2011), we have used ignition times in the fire area, calculated based on the distance from a known ignition point to the perimeter, while use of the reinitialization equation was proposed in Mandel et al. (2012). Our current approach consists of reversing the direction of time in a fire spread method, thus shrinking the fire to one or more ignition point. We have first developed a new fire spread method, which determines the ignition time at a node as the earliest time the fire can get to that node from the nodes that are already burning (Fig. 2a). Such methods are known as minimal travel or minimal fire arrival time (Finney, 2002). A list of nodes on the boundary of the already burning region is maintained similarly as in the fast marching method (Sethian, 1999). The additional complication here is that the fire travel time from one node to the next changes dynamically, because it depends on wind at the moment through the spread rate. To build the artificial fire history, we reverse the direction of the time, start from nodes nearest to the perimeter, and proceed inside the domain. The ignition time propagates to nodes that were not already processed as the maximum ignition time given the ignition times already known, instead of the minimum arrival time (Fig. 2b).

Simulation results for an ideal example show that the fire can continue in a natural way from the perimeter ignition (Kondratenko et al., 2011). Here we demonstrate perimeter ignition on the simulation of the 2007 Santa Ana fires from Kochanski et al. (2013c). These are two fires, Witch and then Guejito, which merged quickly into one massive fire. The perimeter from the simulation at 20:00:00 2007-10-22 is in Fig. 3a, and the artificial ignition time created is shown in Fig. 3b. The artificial ignition graph has two minima, which correspond to the two ignition points and times. Fig. 4 is shows a comparison of the wind from the original simulation and with the artificial ignition times. We have then continued the simulation for additional 6 hours to assess the effect of the perimeter ignition on further propagation of the fire (Fig. 5). Again,
the original simulation, which plays the role of the truth here, and the simulation started from the perimeter ignition, are quite close.

5 Coupling with smoke transport and chemistry

Fire emissions from SFIRE can be input into WRF-Chem (Grell et al., 2005) as chemical species, or into the WRF dynamical core as passive tracers. Chemical species are available only when WRF is built with the CHEM component, while the smoke representation in a form of tracers are available even in the base WRF code. This has a significant advantage, because the full WRF-Chem execution is very computer time intensive, and setting up the model is much more difficult. Both kinds of fire emissions are treated in SFIRE the same way, transparently to the user.

The chemical emissions from a fire are modeled as the mass of the fuel burned times the emission factor for each species, specified in a table given in file namelist.fire_emissions. Files with emission factors from FINN (Wiedinmyer et al., 2011) for the RADM and MOZART chemical models, supported by WRF-Chem, are supplied with the code. The table contains one line for each chemical species, with the amount of per kg of fuel burned for each fuel category. Gas emissions and particulate emissions (PM2.5 and PM10) are given in g/kg, non-methane organic carbon emissions in mol/kg. In every time step, the mass of emission of every species from the fuel burned during the time step, is converted to appropriate concentrations in the first layer of cells in WRF (mol/mol for chemical compounds and µg/kg of dry air for aerosols and particulate matter), and added to the state array chem. This array contains the concentrations of the chemical species advected by the atmosphere and subject to chemical reactions.

WRF, with or without Chem, can be run with 8 tracers, named tr17_1 to tr17_8, by setting tracer_opt=2 in file namelist.input. Concentrations of the tracers are stored in the state array tracer just like for the chemical species. Tracer tr17_1 is simply advected by the wind field; the other tracers have various special properties, described in the comments at the beginning of file WRFV3/chem/module_input_tracer.F (as of WRF 3.4 and 3.5). Emission factors for the tracers are specified in the file namelist.fire_emissions just
like for the chemical species, in units of g/kg of fuel burned, in each fuel category, converted to µg/kg of dry air in the first layer of atmospheric mesh cell, and added to the array tracer.

See [OpenWFM (2013)](http://openwfm.org) and [Kochanski et al. (2013b)](https://doi.org/) for more details on use, further justification, and experimental results. Fig. 6 illustrates the simulation of emissions from a large fire.

It is noteworthy that the described coupling includes also integration with aerosol schemes. Depending on the selected options the chemical species emitted form the fire may react in the atmosphere, leading not only to secondary pollutants formations but also to secondary aerosols. The chemical species emitted and formed in the atmosphere, as well as primary and secondary aerosols, may impact radiative and microphysical process, thus adding new levels of coupling between the fire and the atmosphere.

6 Fuel moisture model

This section is based on the extended abstract [Kochanski et al. (2012)](http://link.springer.com/article/10.1007%2Fs10540-012-9794-9), where more details can be found; see also [Mandel et al. (2012)](http://doi.org/10.1007/s10540-012-9794-9).

Fire spread rate depends strongly on the moisture contents of the fuel, therefore modeling fuel moisture is important. Following the model from [Van Wagner and Pickett (1985)](https://doi.org/10.1007/s10540-012-9794-9), over a long time in constant temperature $T$ (K) and relative humidity $H$ (%), the water contents $m$ in dead wood will approach the drying equilibrium

$$E_d = 0.924H^{0.679} + 0.000499e^{0.1H} + 0.18(21.1 + 273.15 - T)(1 - e^{-0.115H})$$

when starting from $m > E_d$, and the wetting equilibrium

$$E_w = 0.618H^{0.753} + 0.000454e^{0.1H} + 0.18(21.1 + 273.15 - T)(1 - e^{-0.115H})$$
when starting from \( m < E_w \). The evolution of the fuel moisture in time is then modeled by the time-lag differential equation with characteristic lag time \( T \),

\[
\frac{dm}{dt} = \begin{cases} 
\frac{E_d - m}{T} & \text{if } m > E_d \\
0 & \text{if } E_d > m > E_w \\
\frac{E_w - m}{T} & \text{if } m < E_w
\end{cases}
\]

(D3)

During rain, the equilibrium moisture \( E_d \) or \( E_w \) is replaced by the saturation moisture contents \( S \), and equation (3) is modified to achieve the rain-wetting lag time \( T_r \) for heavy rain only asymptotically, when the rain intensity \( r \) (mm/h) is large:

\[
\frac{dm}{dt} = \frac{S - m}{T_r} \left( 1 - \exp \left( -\frac{r - r_0}{r_s} \right) \right), \text{ if } r > r_0,
\]

(4)

where \( r_0 \) is the threshold rain intensity below which no perceptible wetting occurs, and \( r_s \) is the saturation rain intensity. At the saturation rain intensity, \( 1 - 1/e \approx 63\% \) of the maximal rain-wetting rate is achieved. We have calibrated the coefficients to achieve a similar behavior as the rain-wetting model in the Canadian fire danger rating system (Van Wagner and Pickett, 1985), which estimates the fuel moisture as a function of the initial moisture contents and rain accumulation over 24 hours. For 10-hr fuel, we have obtained the coefficients \( S = 250\% \), \( T_r = 14 \text{ h} \), \( r_0 = 0.05 \text{ mm/h} \) and \( r_s = 8 \text{ mm/h} \), cf., Fig. 7.

The model maintains the fuel moisture contents \( m_k \) at the center of each atmospheric grid cell on the surface for several fuel classes \( k \), such as 1-hour, 10-hour, 100-hour, and 1000 hour fuel. Because the atmospheric mesh is relatively coarse, this is quite cheap, and we also avoid any difficulties with nonhomogeneous fuel distribution, because the model is independent of the fuel map. The actual fuel is assumed to be a mixture of those classes in known proportions \( w_k \geq 0 \) given by the fuel category. The fuel moisture contents in each cell on the (finer) fire mesh with is then obtained by interpolating the moisture content \( m_k \) to the finer grid for each fuel class, and then computing the weighted average \( \sum_{k=1}^{N} w_k m_k \).

Because the model needs to support an arbitrarily long time step, we have chosen an adaptive exponential method to integrate the fuel moisture equations at every grid node. Equations

\[ \frac{d m}{d t} = \frac{E - m}{T}. \quad (5) \]

On the time interval \([t_n, t_{n+1}]\), we first approximate the coefficient \(E\) and \(T\) by constants \(E_{n+1/2}\) and \(T_{n+1/2}\) by averaging the atmospheric state variables at \(t_n\) and \(t_{n+1}\), and then solve the resulting constant coefficient equation exactly over the time step interval \([t_n, t_{n+1}]\),

\[ M_{n+1} = M_n + (E_{n+1/2} - M_n) \left(1 - e^{-\Delta t/T_{n+1/2}}\right), \quad \Delta t = t_{n+1} - t_n. \quad (6) \]

For short time steps, \(\Delta t/T_{n+1/2} < \varepsilon = 0.01\), the exponential in (6) is replaced by the Taylor expansion \(1 - e^{-x} \approx x\) to avoid a large relative rounding error caused by subtracting two almost equal quantities. The resulting method is exact for arbitrarily large \(\Delta t\) when the coefficients are constant in time, and it is of second order as \(\Delta t \to 0\).

7 Assimilation of RAWS fuel moisture data

This section follows (Vejmelka et al., 2013) with some simplifications. To assimilate the moisture measurement into the differential equations (3) for each fuel class at each grid point, we augment the model state \((m_k)_{k=1,...,N_k}\) by perturbations \(\Delta E\) and \(\Delta S\) of the equilibrium moisture values: We replace \(E_d, E_w, \) and \(S\) in (3), by \(E_d + \Delta E, E_w + \Delta E, \) and \(S + \Delta S,\) respectively, and add the differential equations \(d\Delta E/dt = 0, d\Delta S/dt = 0\). We then apply the standard extended Kalman filter to the model in the augmented variables

\[ \mathbf{m}(t_i) = (m_1(t_i), m_2(t_i), \ldots, m_{N_k}(t_i), \Delta E(t_i), \Delta S(t_i)). \]

Note that the common state variables \(\Delta E\) and \(\Delta S\) now couple the evolution of the different time-lag fuel moisture classes together.

We use measurements of 10-hour fuel moisture by Remote Automatic Weather Stations (RAWS), available from [http://mesowest.utah.edu](http://mesowest.utah.edu). However, the RAWS data are available only
at a small number of locations, which generally do not even coincide with grid nodes. We extend the measurements and their uncertainty from several RAWS locations to the whole domain using a trend surface model [Schabenberger and Gotway, 2005, §5.3.1]. We are looking for fuel moisture estimate $Z(s)$ at a location $s$ in the form

$$Z(s) = X_1(s)\beta_1 + \cdots + X_k(s)\beta_k + e(s), \quad (7)$$

where the fields $X_j$ are given fields, called covariates, and the errors $e(s) \sim N(0, \sigma^2)$ independent, with $\sigma^2$ the variance of the so-called microscale variability (the structure of the spatial field too small to be captured by the mesh). Given the measurements $\hat{Z}(s_i), i = 1, \ldots, n$, the coefficients $\beta_j$ are found from the regression

$$\hat{Z}(s_i) = X_1(s_i)\beta_1 + \cdots + X_k(s_i)\beta_k + \varepsilon(s_i) + e(s_i), \quad i = 1, \ldots, n, \quad (8)$$

where the errors $\varepsilon(s_i) \sim N(0, \gamma^2)$ are assumed to be independent, and also independent of $e(s_j)$. The variance $\gamma^2$ models the measurement error at the measurement station locations $s_1, \ldots, s_n$. See Vejmelka et al. (2013) for a generalization when $\gamma^2$ is allowed to be different at different $s_i$.

The solution of the regression problem (8) is obtained as the least-squares solution

$$\beta = (X(s)^T X(s))^{-1} X(s)^T \hat{Z}(s), \quad (9)$$

where

$$\beta = \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}, \quad X(s) = \begin{bmatrix} X_1(s_1) & \cdots & X_k(s_1) \\ \vdots & \ddots & \vdots \\ X_1(s_n) & \cdots & X_k(s_n) \end{bmatrix}, \quad \hat{Z}(s) = \begin{bmatrix} \hat{Z}(s_1) \\ \vdots \\ \hat{Z}(s_k) \end{bmatrix}$$

We then have the well-known unbiased estimate of the residual variance from the residual sum of squares,

$$\gamma^2 + \hat{\sigma}^2 = \frac{1}{n - k} \sum_{i=1}^n \hat{e}(s_i)^2, \quad \hat{e}(s_i) = \hat{Z}(s_i) - (X_1(s_i)\beta_1 + \cdots + X_k(s_i)\beta_k). \quad (10)$$
The mean and the variance of the estimated field \( Z(s) \) are obtained by computing the least squares solution \( \beta \) from (8) and substituting into the trend surface model (7), which gives

\[
E[Z(s)] = \mathbf{X}_1(s)\beta_1 + \cdots + \mathbf{X}_k(s)\beta_k
\]

with the mean-squared prediction error

\[
\text{Var}[Z(s)] = \hat{\sigma}^2 + (\gamma^2 + \hat{\sigma}^2) \mathbf{x}(s)^T (\mathbf{X}(s)^T \mathbf{X}(s))^{-1} \mathbf{x}(s),
\]

where \( \mathbf{x}(s) = [\mathbf{X}_1(s), \ldots, \mathbf{X}_k(s)]^T \).

We use \( k = 8 \) covariates. The first four covariates are taken to be the current forecast of 10-hour fuel moisture, air temperature at 2 m, the surface pressure, and the current rain intensity, which capture the effect of the local state of the atmosphere on the fuel moisture equilibrium. The remaining covariates are the terrain elevations, and three independent functions linear in space, taken as the longitude, the latitude, and a constant.

8 Operational use in Israel

The Israeli national fire forecasting system at Weather It Is, LTD, is built on top of WRF-SFIRE. It is based on a complete WRF mesoscale weather forecast for Israel (Fig. 8). In order to be able to produce a fire forecast on demand, the weather forecasting system is running from NWS data 4 times daily, with hourly output WRF forecast, from which the fire forecast is made. The WRF forecasts are at 1.333 km resolution (higher than the NWS forecasts), and then they are downscaled further to 444 m by the ndown.exe utility in WRF. The coupled atmosphere-fire model then runs with 444 m atmospheric mesh resolution and 44.4 m fire mesh resolution. These forecasts can provide high-resolution forecast of not only fires, but severe weather winds/hail, precipitation fields, and terrain-sensitive snow amounts.

The fire forecasting system works interactively. When a fire is detected, the user pins the location of the fire by clicking on the interactive map (Fig. 9), or enters the location numerically. The web site then notifies the server system that a WRF-SFIRE forecast has been requested.
Given the ignition point, a python script on the server generates a series of namelists with the correct parameters describing the fire simulation domain, which is of the size 36x36 cells on the atmospheric 444m mesh, and 360x360 cells on the fire 44m mesh. The ignition point is as close to the center as possible. Static surface data on the fire simulation grid are generated and downscaled data from the 1.333km simulation are added. The moisture model is run from the operational 1.333km system’s output every 24 hours, interpolated to 444m, and inserted in the fire simulation input for every 1 hour simulation interval.

In about 10-12 minutes, the first hour of the forecast is produced, and within 30 minutes a six hour fire forecast is staged for download on the website. In addition to animations, the website also creates Google Earth-based maps of fire spread, intensity, and area coverage. Screen snapshots from the forecast of a small fire in Israel are in Figs. 10 and 11.

The fuel maps are an aggregate of three sources: GIS map of forests from the Jewish National Fund (JNF)’s field operations overlaid by GIS land use map from Israeli national archives. Both are at 61m resolution. The third source is the USGS 1km resolution map, which pads the missing data around the Israeli border and inside the Palestinian authority.

The system also provides a forecast of the fire danger, based on the fireline intensity of a potential fire, for the worst-case scenario at which the fire propagates in the direction that results in the highest fire spread rate for the given wind and slope (Sec. 3). This intensity is computed for each cell on the fire simulation grid using the fuel category in the cell, fuel moisture, and local atmospheric conditions. However, to simplify the interface, only values rescaled to the range 0 to 5 at several landmark points are presented to the user (Fig. 12), instead of a map.

The WRF-SFIRE system can provide a valuable and helpful tool to users, and currently it is the only one running operationally. In addition, the weather forecasts themselves are not standard NWS products and put the weather at the scale of the fire attack crews. The system is delivered to subscribers in the firefighting community and other users in Israel to forecast the fire spread and assess the difficulty of suppression and fire danger (Regev et al., 2012).
9 Summary and Conclusions

WRF-SFIRE system has significantly evolved since its original description was published in (Mandel et al., 2009, 2011a). The originally simple fire modeling framework advanced by new components that significantly expanded the original capabilities of WRF-SFIRE. The coupling between the atmospheric component of the system and the fuel moisture model allows now for modeling the fire spread, taking into account changes in the fuel properties driven by the weather conditions. In the current form, the model not only creates a weather forecast, but also a fuel moisture forecast, which is used by the fire component of the system to simulate the fire behavior. This new level of interaction embedded into the WRF-SFIRE modeling system has a potential to improve fire behavior representation under conditions when temporal changes in the fuel moisture become important. The model does not assume any diurnal variation in the fuel moisture or intensity. Instead, basic atmospheric properties including temperature, humidity, precipitation, and winds are used for the computation of the fuel moisture and the fire spread at any given time. The fuel moisture component of the system is also used as the core of a fuel moisture data assimilation system, which creates the best estimate of the fuel moisture state, generated, in a gridded form, by a fusion of the observed fuel moisture with the moisture model estimates.

The updated version renders also the fire smoke. Depending on the users’ requirements, it can be simply treated as a passive tracer advected in the dynamical core of the WRF model, or represented as a mixture of chemically reactive species emitted into the atmosphere, and undergoing chemical and physical reactions. The latter approach, requiring building the model with WRF-Chem, allows not only studying the fire and smoke emission and dispersion, but also investigating the effects of smoke on the atmospheric chemistry. The coupling between the fire model and the chemistry provides a new framework for simulating secondary pollutants created in the atmosphere from the species emitted directly by the fire. Thus, this new functionality allows for rendering the air quality effects of the fire emissions.

The integration with the WRF-Chem is not limited to chemical species. The primary aerosols, and creation of secondary aerosols may be captured with this framework as well. The aerosols
emitted by fires may interact with radiation and microphysical processes allowing for another level of coupling between the fire and atmosphere, needed for example in order to study processes related to creation of pyrocumulus clouds.

The original ignition mechanism allowing for point and line ignitions has been expanded by the ignitions from an arbitrary fire perimeter. This new functionality allows for continuing the fire spread progression from the observed fire contour, without a need for starting the whole simulation from an initial ignition point or line.

In conclusion, advances in the WRF-SFIRE system include coupling with models of selected other components of the Earth system, which have significant impact on fire behavior (moisture) or are significantly impacted by fire (atmospheric chemistry). Improvements have been directed also towards increasing usability in practice (interfaces with GIS, fire danger assessment, and ignition from perimeter). A new concept of fireline intensity was also presented. WRF-SFIRE benefits from the integration with WRF, the widespread use of WRF, distribution in the public domain, the general knowledge of operating WRF in the atmospheric science community, and it leverages the standard WRF inputs and outputs.

As a consequence, WRF-SFIRE became one of the first coupled fire-atmosphere models implemented operationally. The newly added capabilities in terms of smoke and fire emission prediction made it an all-in-one model with a potential of generating fire spread, fire emission, plume rise, plume dispersion, and air quality forecast within one integrated framework.

Future work will expand the perimeter ignition approach to the assimilation of fire behavior data, particularly fire location from remote sensing. Addition of the new fire spread models as well as mechanisms for integration with other systems like Blue Sky and CMAQ are also planned.

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References


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Fig. 1. The overall scheme of WRF-SFIRE.
Fig. 2. (a) Propagation of ignition time $t$ to a node from neighboring nodes already on fire. (b) Backtracking (propagation back in time) of ignition time to a node from neighboring nodes where the fire arrived later.
Fig. 3. (a) Perimeter of the 2007 Santa Ana fires simulation at 20:00:00 2007-10-22. (b) Artificial ignition time found by fire propagation back in time from the fire perimeter in (a). The two peaks on the bottom are the two ignition locations and times, found automatically from the perimeter.
Fig. 4. (a) Horizontal wind at 6.1m in the 2007 Santa Ana fires simulation at 20:00:00 2007-10-22. (b) The same wind as in (a), but with the artificial ignition time history from Fig. 3 until 20:00:00 2007-10-22.
Fig. 5. (a) Fire perimeter in the 2007 Santa Ana fires simulation at 04:00:00 2007-10-23. (b) The same perimeter as in (a), but with the artificial ignition time history from Fig. 3b until 20:00:00 2007-10-22.
Fig. 6. Illustration of smoke transport and dispersion from a simulation of 2007 Santa Ana fires by WRF-SFIRE coupled with WRF-Chem. Shown are the boundary layer circulation in the plume and PM25 concentration.
**Fig. 7.** Response of fine fuels to rain over 24 hours (a) following Van Wagner and Pickett (1985) (b) from the time-lag model (4) by a calibration of coefficients.
Fig. 8. Weather forecast for Israel, which serves as a basis for the fire forecast. Wind and temperature shown to the user.
Fig. 9. Interactive fire ignition.
**Fig. 10.** Fire area and fireline forecast for a small fire in Israel. Fire area 1.0 means that the whole grid cell is burning.
Fig. 11. Forecast of fire rate of spread in the vicinity of the fireline.
Fig. 12. Fire danger forecast, based on the fireline intensity of a potential fire propagating in the direction with the maximum rate of spread.