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Establishment of a wildfire forecasting system based on coupled weather–Wildfire modeling

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ABSTRACT

The Weather Research and Forecasting model (WRF) includes a wildland fire-behavior module, WRF-Fire, which simulates wildland fire interactions with the atmosphere. Combining the WRF model with the coupled weather–wildland fire model allows simulations of wildland fire propagation. In this paper, we have chosen the method that performs simulation of wildfire spread progress coupled with prepared weather data as soon as a wildfire is found. In simulation of the weather field data, a one-way nest model is used with a grid resolution of 1 km. The high-resolution Digital Elevation Model (DEM) data ($0.002^\circ \times 0.002^\circ$) and fuel distribution maps based on forest type data were used. We demonstrated the potential for establishing a real-time wildland fire forecasting system using WRF-Fire model based on the existing conditions and computing resources for weather condition at fire monitoring stations, which can be applied in monitoring and forecasting of the wildland fire disasters in the area of the country.

1. Introduction

Accurate forecasts of wildfire propagation are vitally important for wildfire management, including the emergent response to the wildfire through setting wildfire warning system and evacuation buffers (Larsen, Dennison, Cova, & Jones, 2011). Wildfire forecast models typically evaluate the possibility of fire reaction with various fuels (vegetation) on a landscape and analyze fire interactions with atmospheric and climate factors to guide firefighting operations (Anderson, 1982).

A number of wildfire forecasting and fire simulation studies have been developed based on work in different areas of the world (Balia, Serra, & Modugno, 2011; Coen, 2005; Dobrinkova, Jordanov, & Mandel, 2010; Finney, 1998; Peace & Mills, 2012; Peace, Mattner, & Mills, 2011). Many of these studies have evaluated the effectiveness of the wildfire module (SFIRE) in the Weather Research and Forecasting model (WRF) (NCAR, 2012). SFIRE is a non-static, compressible model consisting of a continuity equation, thermodynamic equation, and water vapor equation, which anticipate wind speed, temperature, water vapor, cloud water, rain, and ice water, etc. in a three-dimensional grid. SFIRE uses an Arakawa C-grid in the horizontal direction and a dynamic vertical coordinate with topography in the vertical direction. This model has multiple nested functions, enabling to establish various finer grids within coarse grid spacing. Thus, it can well simulate how a three-dimensional atmospheric flow structure varying in time influences a wildfire.

Wildland fire modeling can simulate the development, spread, and suppression of a wildfire, and also describe the rate of wildfire spread as well as the heat released in the burning of fuel in two dimensions. Wildland fire modeling deals with three physical processes: the rate of spread of the wildfire perimeter (boundary between burning fuel and unburned fuel), the release of heat in a wildfire area, and scale extension to convert released heat into the atmospheric model. Because physical processes occur on much smaller scales than is captured by the grid and time step of the atmospheric model, semi-empirical formulas are used for parameterization of the sub-grid scale in wildfire simulations (Mandel, Beezley, & Kochanski, 2011b). The wildfire perimeter advances for each time step as unburned fuel ignites and more fuel is consumed in areas that have already ignited. Atmospheric models are relatively coarse, with high-resolution only for the actual wildfire area. Release of heat is determined as a function of time of ignition, fuel properties, and atmospheric conditions.

Using WRF-Fire, coupled weather–wildland fire modeling with

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WRF, and the wildfire behavior module for predicting wildfire, the influences of a wildfire on the atmosphere and the influence of atmospheric conditions on the wildfire can be simulated. In WRF-Fire, characteristics of the atmosphere and wildfire modules are exchanged in each time step. In the atmosphere module, the influence of the wind field on the wildfire rate of spread is calculated (Coen et al., 2013). Clark, Coen, and Latham (2003) showed a detailed interpretation of the WRF-Fire model through various experiments. They diagrammatically examined the propagation direction and the rate of fire spread, focusing specifically both on the uncoupled model, which did not consider the ambient wind effect. The results demonstrated that uncoupling was possible in a relatively simple fire simulation. They also concluded that more meteorological fire simulations can be realized using a coupled atmosphere-fire model. Kochanski et al. (2010) simulated fire plumes using a coupled atmosphere–fire model based on the ARW atmospheric core and the Rothermel fire model (Rothermel, 1972). Their results showed that the background flow characteristics were not well simulated at higher elevations where flows were away from the surface and did not affect the fire. Beezley, Kochanski, Kondratenko, Mandel, and Sousedik (2010) found that simulated results showed more rapid propagation and fire spread than actual observations in fire spread, and more detailed fuels models and moisture component data were needed to overcome these errors. Clark et al. (1996a,b) provided a more detailed description of the coupled atmosphere–fire model. Coen (2005) also reported an experiment for simulating fire using the Big Elk Fire as an example.

Clark et al. (1996a,b) used the coupled atmosphere–fire model to conduct a more in-depth study of fire spread simulations. Their results showed that if the wind speed was relatively low, the coupling between the atmosphere and the fire was strengthened and the rate of fire spread increased with wind speed; however, if the wind speed was high, the coupling between atmosphere and fire was rather weakened. This was especially true when the wind speed was more than 10 m/s. In contrast, the coupling between the fire and its induced motion weakened and decoupling between the fire and atmosphere occurred. Another study found that turbulence in the atmospheric boundary layer, which is highly affected by the ground surface, plays an important role in fire spread (Sun, Krueger, Jenkins, Zulauf, & Charney, 2009). A simulation of the effect of ambient wind on the fire spread speed by Beer (1991) showed that the fire propagation speed was more than 50% faster in wind conditions of 2–6 m/s when atmospheric conditions were unstable. Other results have shown that the background wind profile is very important for simulating fire propagation, which is dependent on low pressure associated with the development of vortices (Kochanski, Jenkins, Mandel, & Beezley, 2012b).

Near-surface wind is input from the atmosphere module to the wildfire module, which determines spread rate and direction as well as fuel conditions and topographic gradient. A simulated wildfire consumes fuels, including living and dead plants, and releases heat and water vapor to the air. Wind blown into the flame is changed under wildfire conditions. The wildfire module calculates fuel consumed and energy released by the wildfire and transfers this information to the atmospheric variable. On the lowest layer of the atmospheric model, energy released during the wildfire is transferred to the sensible and latent heat variables of the atmospheric model equations. Simpson, Sharples, Evans, and McCabe (2013, 2014) used the WRF-Fire model to investigate vorticity-driven lateral fire spread (VLS) and reported that both high spatial resolution for simulating fire spread and the two-way coupled atmosphere-fire model are important components for modeling VLS using the atmosphere–fire model.

There have been a series of studies aimed at numerically simulating the development of fire under specific conditions using the WRF-SFIRE model, which consists of the Weather Research and Forecasting (WRF) model coupled with the fire-spread model (SFIRE) (Kochanski, Beezley, Mandel, & Kim, 2012a, 2012b; Mandel, Beezley, & Kochanski, 2011a; Mandel et al., 2014a,b; Vejmelka, Kochanski , & Mandel, 2013). Vejmelka et al. (2013) suggested a method for obtaining a moisture map of various flammable substances by assimilating data on the state of the atmosphere from remote automatic weather stations (RAWS) into WRF-SFIRE. Kochanski et al. (2012a) described a newly added WRF-Chem coupling model for fire simulation, and this model reveals that fire behavior can be treated as the dynamic flow of various gas combustion materials.

Mandel et al. (2014a) provided a more detailed study of the WRF-SFIRE model. They showed that the coupling between the fire model and atmospheric chemistry was effective in improving simulations of fire and air quality, and also emphasized the possibility of using the model in other studies of atmospheric chemistry. Another study described a new assimilation method for active detection of fire based on the modification of fire arrival time using a Bayesian inverse problem technique (Mandel et al., 2014a,b).

Our study evaluated the potential for application of WRF-fire over an area in the DPRK based on prior theoretical research and numerous simulations for managing fire.

2. Atmospheric model settings and implementation

Wildfires are affected by complex and multi-scale weather and climate processes (Fox et al., 2015; Mandel et al., 2011b). Wildfire spread simulation requires meteorological fields with high-resolution. However, the higher the resolution is, the more time it requires. The purpose of wildfire forecasts is to provide rapid assistance to fire managers by predicting the direction of fire evolution. However, this requires too much computational time to use the optional run. Therefore, it is important to set the nesting domain and scale of resolution.

2.1. Nesting domains and resolution in the atmospheric model

WRF supports a multi-grid nesting configuration, and the standard coarse-to-fine grid ratio is 3. The coupled atmosphere–fire model is run in only the finest mesh. Four nested domains are required to scale the simulation down from atmospheric initialization (25 km) to the fire grid resolution (about 1 km) (Table 1). In this case, it required a great deal of time to generate a 24-h forecast. Thus, we used a one–way nesting run configuration. In one-way nesting, the parent-to-child grid ratio is 5. The construction of nested grid domains was as follows.

Model run outputs were obtained by running WRF in every analysis time step for the two domains shown in Fig. 1. The fire spread simulation was started from the time the fire was discovered in a satellite image. Mandel et al. (2014a) proposed a method of assimilating satellite data into wildfire simulations to provide fire updates using satellite image data.

We ran the WRF-SFIRE model with a grid resolution of 1 km and the domain determined in a given grid dimension with fire position as the center. The fire grid refinement was 10. A two-dimensional fire propagation model was run in finer mesh with grid spacing of 100 m subdivided by 10 times based on the 1 km-resolution atmosphere–fire model.

2.2. Calculating meteorological data using one-way nesting

First, geogrid and metgrid were run for two domains as two-way

Table 1
The resolution of atmospheric model for fire spread simulation.

Domain	Grid spacing (km)	x-grid dimension	y-grid dimension	Vertical dimension
d01	25	80	80	35
d02	5	141	141	35
d03	1	40	40	69

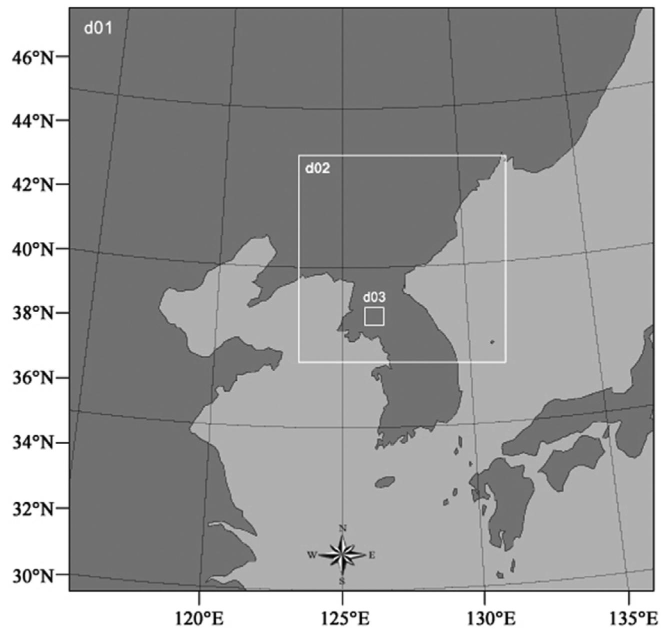

Fig. 1. Domains chosen for obtaining meteorological data. D01: Domain One; d02: Domain Two; do3: Domain Three.

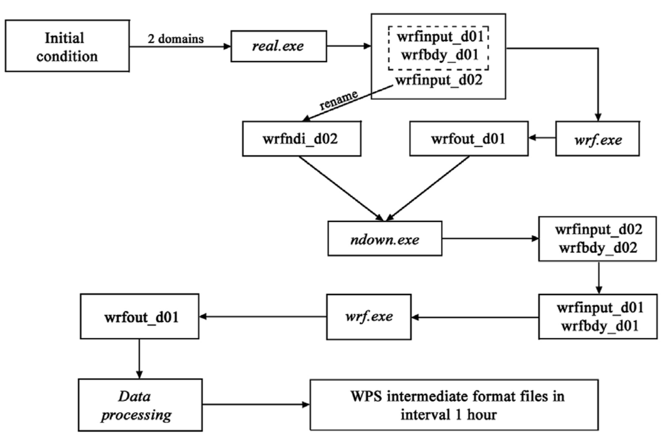

Fig. 2. One-way-nested configuration of multi domains.

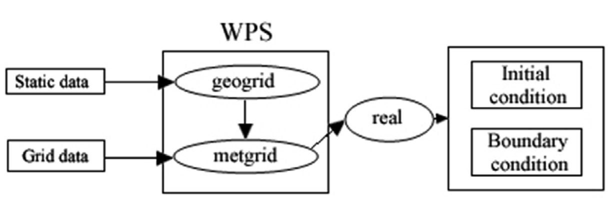

Fig. 3. Schematic diagram of WRF preprocessing system.

nesting with *namelist.wps* and *namelist.input* edited with horizontal grid spacing of 25 km and 5, respectively. Then, the two initial and boundary condition files were obtained from a *real.exe* run.

Second, we ran the model (wrf.exe) in the outer nest (parent's nest) for 24 h and obtained the WRF output of domain 1 (wrfout_d01). Then, we used the model output and the initial condition (wrfinput_d02) in the second domain to run *ndown.exe* to get a new initial condition for the second domain. A 24-h forecast output file for the second domain was obtained using the initial condition. The output interval time was one hour. The parameter file (*namelist.input*) must be edited in every step. In cases in which the fire position, size, and ignition time are known, simulations must be carried out from the time of ignition (result

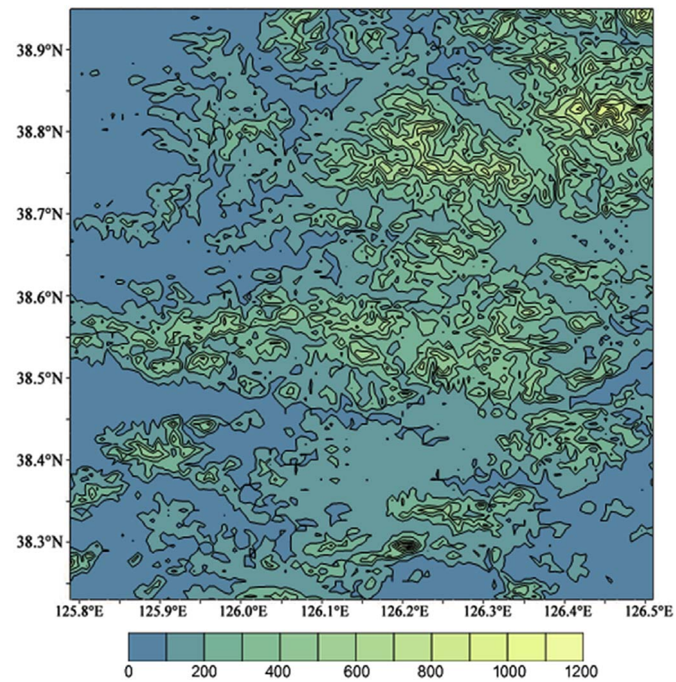

Fig. 4. The topographical conditions of the simulated area (Domain Three in Fig. 1). Unit of elevation: m above sea level.

of sufficient model stabilization step) so that the amount of calculations can be reduced.

In the operational run, there are two analysis processes per day (00UTC, 12UTC). So, when the analysis data is obtained, the NWP model run produces output at intervals of one hour, meaning the fire can be simulated using any starting time for fire ignition. The WRF meteorological output is then converted to WPS intermediate files.

Fig. 2 shows the process of obtaining the meteorological data (with 5 km horizontal grid spacing) necessary to run the coupled WRF-Fire model.

3. WRF-fire model settings and implementation

3.1. Building a static database (high resolution topography and fuel data)

The wildfire simulation is carried out considering topographical and fuel factors. Therefore, it is necessary to build static databases for the high-resolution topographic and the fuel data that can be used in the WRF model. In wildfire simulations, topographical conditions have as much significance as atmospheric conditions. In particular, simulations of the paths of spread for a wildfire require sufficient coupled conditions of atmospheric conditions and terrain (Sharples, Mcrae, & Wilkes, 2012). The static database is read when *geogrid.exe* is executed in the WRF Preprocessing System (WPS) to generate static data for the wildfire forecast area (Fig. 3).

We created the topography and fuel databases using a series of steps. We made a binary file written as a geogrid format using DEM data for the DPRK area with 0.0002° spacing (20–30 m grid spacing). A 5000 × 5000 array (dataset of 1° × 1° domain) was written for each data file. The fuel database consisted of five classes of fuel data from the National Forest Survey, which was numerically coded according to tree species. The classes of fuel data from the National Forest Survey include Grass, Chaparral, Brush and Litter. In some areas of DPRK, Slash in Anderson fuel categories (Anderson, 1982) can hardly be seen. Therefore, we set the corresponding relation between Anderson 14 fuel categories and the fuel categories, considering fuel weights and total fuel loads. The 5 fuel categories used are: 1-Grass (Anderson categories 1-3average), 2- Chaparral (Anderson category 4), 3- Brush (Anderson

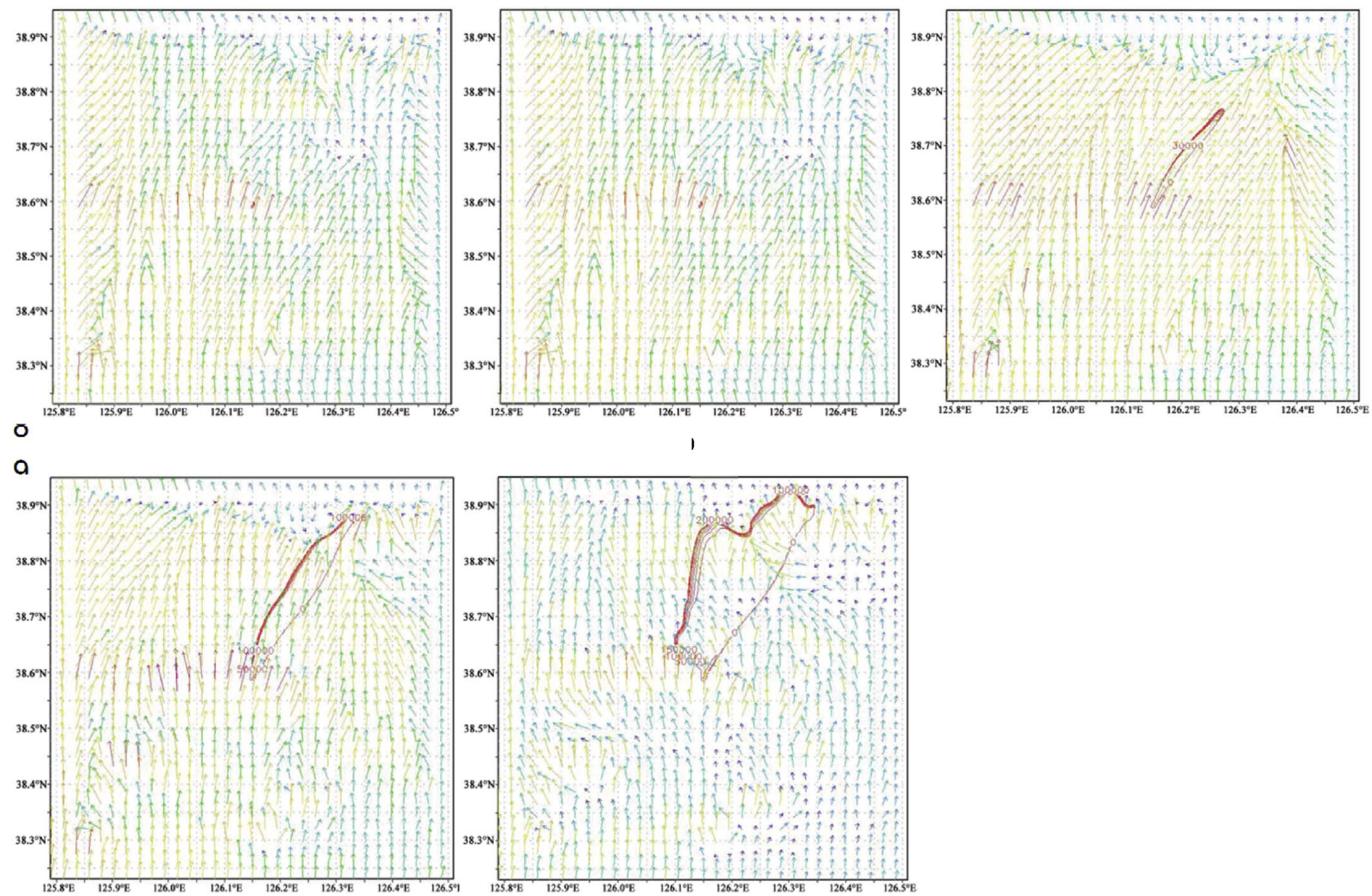

Fig. 5. Fire spread after different time periods in the simulated area (Domain Three of Fig. 1). a, b, c, d, e denote the simulated fire spread after 150s, 300s, 450s, 540s and 600s of the fire ignition.

category 5), 4- litter (Anderson categories 8-10average), 5- no fuel (Anderson category 14).

Besides the binary data files, the geogrid requires an extra metadata file (named “index”) for each data set. The geogrid produces static data based on the list of the *GEOGRID.TBL* file. Therefore, we edited the list of topographic and fuel data (*ZSF* and *NFUEL_CAT*) in the *GEOGRID.TBL* file.

3.2. Implementation of the fire-model

The fire-model was executed according to the following steps:

Step 1. We edited the fire mesh domain information in *namelist.wps* based on the fire-center position (longitude and latitude coordinates), fire size (the radius of fire area, m), ignition time (yy/mm/dd/hh) obtained from the fire guard. As mentioned above, we defined 1 km of meteorological calculating domain grid spacing and 40 × 40 of horizontal dimensions in the coupled atmosphere–fire model. We recommend using a fire mesh refinement ratio of 10 (subgrid_ratio_x = 10, subgrid_ratio_y = 10); fire mesh grid spacing was 100 m.
Step 2. We ran geogrid and metgrid, and generated metgrid files combined with meteorological data and static data.
Step 3. We edited *namelist.input* and executed it for generating the initial and boundary files necessary to run the model. We recommend setting vertical layer numbers to 50 (vert = 50) to keep the difference between the lowest layers small. If the difference is large, the wind field for calculating fire propagation will be interpolated too large than the actual case.

Because the fire model is 2-dimensional based on the effects of wind and topographic factors, the effect of physical processes on fire propagation is relatively small. However, calculation of physical processes in the model run takes a lot of time. Therefore, we disabled options for physical processes (microphysics processes and longwave and shortwave radiation processes). We recommend the option *isfflx = 1*, which makes WRF use a surface model to compute the surface fluxes. Other options for constant heat fluxes and drag are not well suited for fire simulations. Out of all surface exchange parameterizations, only the classic Monin-Obukhov theory (sf_sfclay physics = 1) is recommended for the LES cases. We defined time_step = 6 in order to satisfy CFL conditions because the fire mesh grid spacing is 1 km.

4. Simulation results and discussions

The fire forecast system was run immediately after the location of fire ignition was confirmed from an information source such as satellite data. We simulated the spread progression of the perimeter of the fire with a 1000 m radius that occurred at 38.53°N, 125.75°E at 12:50, Mar 28, 2016. The topographical conditions of the simulated area are shown in Fig. 4, and the fire spread area and wind vectors are shown in Fig. 5.

In the optional run, a model run for obtaining meteorological data with 1 km mesh grid is carried out twice every day (requires 20min using a PC-i7). When a fire occurs, a fire model is run in 40 × 40 km domains centered on the fire position. It takes about 15 min to generate a 24-h forecast.

The meteorological field can be obtained optionally by using a one-way nested configuration in every analysis process. Then, whenever a fire occurs, the WRF-Fire model is run. In this case, the fire propagation process is simulated in relatively short time using only one PC-i7 computer.

The standard program of the WRF-ARW model does not support coordinate and terrain gradient data in making an initial condition file. Therefore, we inserted codes for calculating coordinates of fire mesh and terrain gradient data in the *real_em* module and fire calculation modules. The results from several simulations showed that fire ignition time was related to fire area size. The larger the fire area, the later the fire ignition time was. For example, fire-burning time was 2 min after time of ignition in the case of a fire radius of 100 m, but about 25min in the case of a fire radius of 1000 m.

In the optional fire guard system, it is possible to monitor a fire with a radius of more than 1000 m because of satellite resolution. Therefore, the fire model was run from an earlier initial condition (before 30min) to simulate fire spread based on the start time.

In the simulations, fire spread behavior was faster than the on-the-ground situation, which was consistent with Beezley et al. (2010). This is because the atmosphere–fire model was run over a coarser mesh. Clark el al. (1996b) found that the simulated fire spread was faster than observation in case of lower resolution. In our simulation, the resolution of atmospheric model was 1 km and the resolution of fire model was 100 m. These resolutions were coarser than the 400 m-resolution atmospheric model and 30 m-resolution fire model in Mandel et al. (2011a). When the simulated spread speed and direction of wildfire and burned area were compared with observation images by the stationary satellite GMS (every 15min) and HIMAWARI (every 10min), and polar orbital satellite NOAA (every 12 h), the previous researches were qualitatively confirmed. However, establishment of a fire spread forecast system that simulates fire spread direction using the low capacity computers available at all fire guard stations is a large contribution in preventing and managing wildfires.

5. Conclusions

The weather field was calculated first for a grid of 1 km, and the calculation was carried out as soon as the wildfire was detected, based on the one-way nested method. The ratio between the atmospheric model and the fire-model grid was 1:10. DEM data of 0.0002° (20–30 m) intervals in both longitude and latitude coordinates were used as high-resolution topographic data.

We showed that the simulated fire spread behavior was faster than the observed spread, probably because the atmosphere–fire model was run over an inadequate mesh condition. Consequently, we explained the influence of the results on establishing a real-time wildland fire forecasting system using WRF-Fire based modeling and the existing computing resources.

We concluded that numerical simulations of fire spread, even under normal facility conditions, have some significance in current fire monitoring conditions. In the future, however, the high-resolution data processing required in the meteorological fire modeling fields should be considered. It would be also interesting to further examine the long-term change in wildfire events and the future risks under the background of global and regional climate change (Fox et al., 2015), and the applicability of the WRF-Fire model in the changing climate condition the study area.

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