

Article

# Development of a Smoke Dispersion Forecast System for Korean Forest Fires

**Boknam Lee**  **Seungwan Cho** <sup>2</sup>, **Seung-Kii Lee** <sup>3</sup>, **Choongshik Woo** <sup>4</sup> and **Joowon Park** <sup>2,\*</sup>

<sup>1</sup> Center for Future Environmental and Forest Resources, Research Institute of Agriculture and Life Sciences, Seoul National University, Seoul 08826, Korea; leeboknam@gmail.com

<sup>2</sup> School of Forest Sciences and Landscape Architecture, Kyungpook National University, Daegu 41566, Korea; one5639@naver.com

<sup>3</sup> MVSofttech Co., Ltd., Daejeon 35225, Korea; skinu@mvsofttech.co.kr

<sup>4</sup> Division of Forest Disaster Management, National Institute of Forest Science, Seoul 02455, Korea; woocs@korea.kr

\* Correspondence: joowon72@knu.ac.kr; Tel.: +82-53-950-5747

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**Abstract:** Smoke from forest fires is a growing concern in Korea as forest structures have changed and become more vulnerable to fires associated with climate change. In this study, we developed a Korean forest fire smoke dispersion prediction (KFSDP) system to support smoke management in Korea. The KFSDP system integrates modules from different models, including a Korean forest fire growth prediction model, grid-based geographic information system (GIS) fuel loading and consumption maps generated by national forest fuel inventory data, and the Korean Weather Research and Forecasting Model, into a Gaussian plume model to simulate local- and regional-scale smoke dispersion. The forecast system is operated using grid-based fires and simulates a cumulative smoke dispersion of carbon monoxide (CO) and  $<2.5\text{ }\mu\text{m}$  and  $<10\text{ }\mu\text{m}$  particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ , respectively) ground-level concentration contours at 30-min intervals during the fire in concert with weather forecasts. The simulated smoke dispersions were evaluated and agreed well with observed smoke spreads obtained from real forest fires in Korea, and the performance of the KFSDP system was also analyzed using “what-if” scenarios. This is the first study to develop an integrated model for predicting smoke dispersion from forest fires in Korea.

**Keywords:** forest fire; smoke dispersion; Gaussian plume model; forecast system

## 1. Introduction

Smoke from forest fires presents a rising problem as it contains large amounts of trace gases and aerosol species [1–3]. The smoke pollutants released by forest fires include greenhouse gases (carbon dioxide ( $\text{CO}_2$ )), methane ( $\text{CH}_4$ ), and nitrous oxide ( $\text{N}_2\text{O}$ )), photochemically reactive compounds (carbon monoxide (CO) and nitrogen oxides ( $\text{NO}_x$ )), and fine ( $<2.5\text{ }\mu\text{m}$ ) and coarse ( $<10\text{ }\mu\text{m}$ ) particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ), which degrade air quality and Earth’s climate system due to their feedback with the global climate change [4–7]. The contribution of emissions from wildland fires worldwide has been estimated to be approximately 40% for CO, 35% for  $\text{CO}_2$ , and 20% for  $\text{NO}_x$  [8], and this contribution is expected to increase due to the number of large fires in the coming decades according to climate change scenarios [9].

Increasing the level of pollutants emitted from fires can also be detrimental to human health. The major health threats related to smoke from forest fires are respiratory problems caused by the inhalation of smoke particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ), which damages membranes in the lungs [10–12]. Such ailments can afflict even healthy people; however, they are especially dangerous

for those with asthma or other chronic respiratory problems, as well as small children. Moreover, it has been reported that the reduced visibility due to particulate matter and other elements in smoke plumes occurs up to hundreds of kilometers downwind from emission sources and disturbs human activities [13,14].

In Korea, there is growing awareness about the hazardous effects of fire smoke dispersion. Since 1970, the success of reforestation projects has resulted in dense forests with more than  $148 \text{ m}^3/\text{ha}$  on average [15,16]. However, with increasing litterfall and biomass, Korean forests have become more vulnerable to fires under ongoing changes in the global climate, which are driving more frequent and larger fires [17]. In Korea, more than 395 fire episodes per year from 2006 to 2015 generated smoke, even if their scales were not massive, resulting in dozens of community evacuations from smoke exposure as well as contributing to the impairment of air quality, and leading to hazardous and inconvenient conditions [18]. For instance, the dispersion of particulate matter from smoke at fire location areas has been extensively deteriorating regional air quality and negatively affecting human health [19].

To better understand and cope with adverse smoke exposure from fires, real-time smoke dispersion prediction systems have been developed as a decision support system for various smoke management communities across the globe. For example, the USDA Forest Service's (USFS's) BlueSky smoke modeling framework had been widely used in the United States (U.S.) and Canada to provide guidance for both prescribed and wildfire smoke management [20–22]. The U.S. National Oceanic and Atmospheric Administration (NOAA) smoke prediction system is another smoke dispersion forecasting system designed to address community air quality needs using satellite fire detection [23]. The ClearSky prediction system (<http://www.clearsky.wsu.edu>) was developed to forecast smoke dispersion, especially from agriculture-related fires in the U.S. Pacific Northwest. In Australia, the Australian Bureau of Meteorology's smoke prediction system was developed to assist land managers in planning prescribed burnings while reducing the impacts of smoke from these fires [24,25].

Smoke dispersion prediction systems require a set of model components to predict the magnitude and location of smoke effects from fires. A series of modeling steps must be processed sequentially from gathering fire information, to quantifying fuel loading, fuel consumption, and smoke emissions, and finally predicting smoke dispersion based on the meteorological data produced from a weather forecasting model. For instance, the BlueSky smoke modeling system (BlueSky) couples off-the-shelf models for fuel (e.g., the Fuel Characteristic Classification System [26]), consumption (e.g., the Emissions Production Model [27]), emission (e.g., the Fire Emission Production Simulator [28]), weather (e.g., Weather Research and Forecasting (WRF) models [29]), and dispersion (e.g., CALPUFF dispersion model [30]) in a modular framework to produce real-time predictions of smoke transport in the U.S. and Canada [20]. However, the model components in BlueSky are only suitable for forecasting smoke dispersion from fires in the U.S. and Canada since the models were developed based on the properties of fire events, fuel characteristics, fuel consumption, and smoke emissions in the those areas.

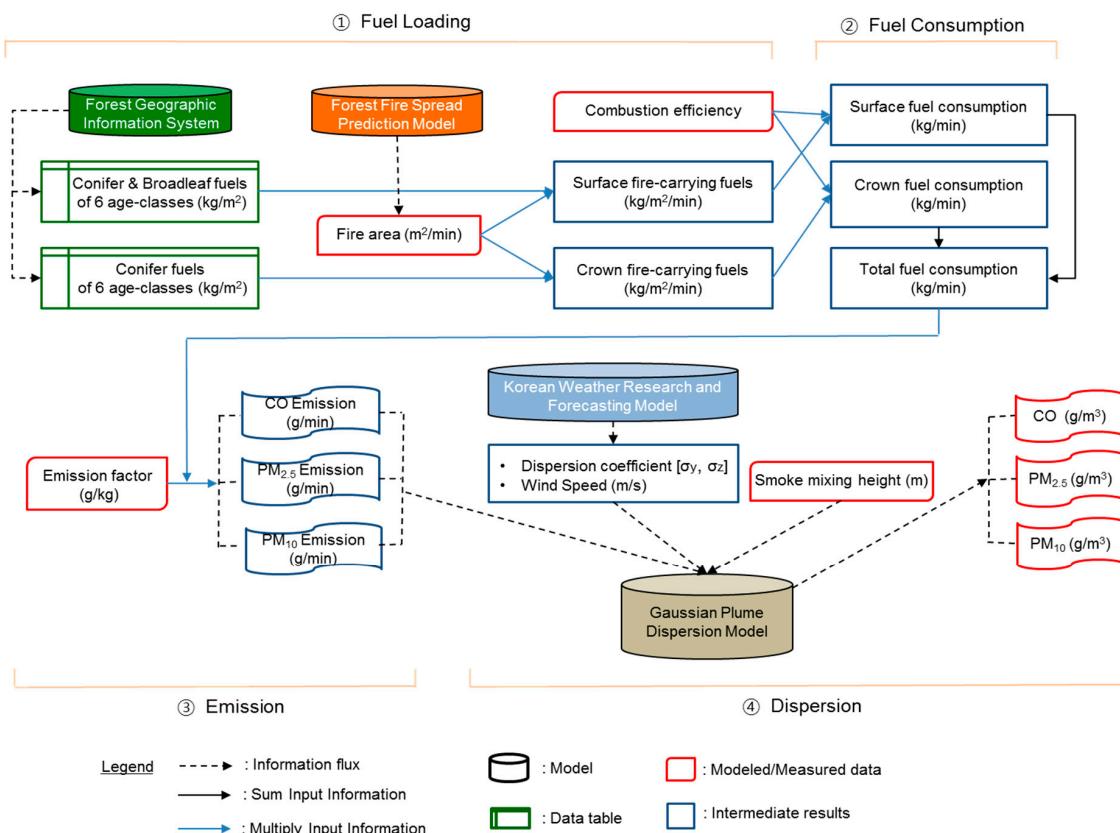
In Korea, no integrated smoke dispersion prediction system yet exists to assist in smoke management. Compared to the large-scale forest fires that have occurred across the globe, such as in the U.S. and Canada, 98.5% of the forest fires that have occurred in Korea have been small-scale fires, most of which burned less than 10 ha [18]. Correspondingly, smoke transport from most of these fires appeared to occur over less than 50 km along the downwind distance according to satellite imagery of the smoke dispersion [31]. Therefore, for proper smoke management in Korea, it was necessary to develop the Korean forest fire smoke dispersion prediction system (KFSDP) by considering the characteristics of fire events, fuel properties, and smoke transport in Korea.

The main purpose of this study was to introduce and describe the development of the KFSDP system and to demonstrate its operating components. The KFSDP is an integrated smoke prediction system designed to forecast local and regional smoke dispersion from forest fires across Korea. It includes six major components, including a Korean forest fire growth prediction model, the geographic information system (GIS) raster layers of forest fuel loading and fuel consumption, an emission model, a Korean Weather Research Forecasting (KWRF) model, and a Gaussian smoke

dispersion model, to forecast smoke concentrations with regard to the ground-level concentrations of CO, PM<sub>2.5</sub>, and PM<sub>10</sub> in real-time. The capabilities of the KFSDP were demonstrated through the evaluation of its performance (i.e., validation) by comparing case studies based on simulated smoke results with measurements from real forest fires, and by analyzing “what-if” scenarios.

## 2. Korean Forest Fire Smoke Dispersion Prediction (KFSDP) System

The main components of the KFSDP system are shown in Figure 1. The KFSDP system integrates major modules from a Korean forest fire growth prediction model, an array of GIS raster layers of forest fuel loadings and consumption generated by National forest fuel inventory data, and a set of weather forecast data produced by the KWRF model. These modules are then incorporated into a Gaussian plume dispersion model (GPDM) to simulate local- and regional-scale smoke dispersion. The forecast system is operated using grid-based fires and sequentially links fire activity data obtained from the forest fire spread prediction model to fuel loadings, consumptions, emissions, and a smoke dispersion model. Within the conceptual framework, we delineated five major modules: (1) a Korean forest fire spread prediction module, (2) a fuel loading module, (3) a fuel consumption module, (4) an emission production module, and (5) a smoke dispersion module that simulates the cumulative smoke dispersion of CO, PM<sub>2.5</sub>, and PM<sub>10</sub> concentrations at 30-min intervals together with weather forecasts.



**Figure 1.** Integrated framework for predicting the smoke dispersion of CO, PM<sub>2.5</sub>, and PM<sub>10</sub> concentration using the Gaussian plume smoke dispersion model. PM<sub>2.5</sub> and PM<sub>10</sub> are fine ( $<2.5 \mu\text{m}$ ) and coarse ( $<10 \mu\text{m}$ ) particulate matter, respectively.

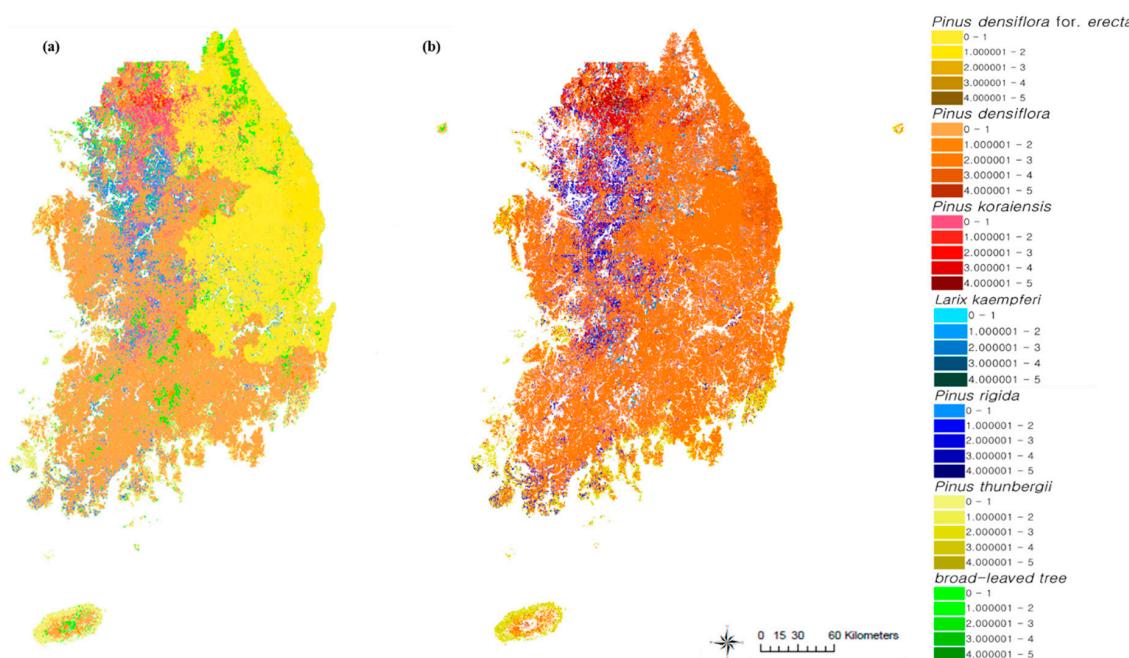
### 2.1. Forest Fire Spread Prediction Model

A forest fire spread prediction model developed by the Korea Forest Institute was used to simulate the growth of fire areas, which was then provided into the KFSDP system as the fire input data. The shape of fire in the fire spread model is described as the ellipse with the long axis aligned in the direction of the wind [32]. The growth of fire is implemented by the expansion of an elliptical wave

front from a series of vertices defining the edge of a fire applied using Huygens' wavelet principle [33]. The rate of fire spread and intensity is modeled by the Rothermel fire spread equation [34]. For the purposes of forecasting, the expansion of fire areas was simulated for 30-min intervals based on a GIS fuel map for entire forests across Korea and weather forecasts obtained from the Korea Meteorological Administration. The simulated outputs of fire growth area were then used for fuel loading estimation in the KFSDP system.

## 2.2. Fuel Loadings

Fuel loadings for each fire area were obtained from a spatial (30-m) fuel property map in the GIS raster layers developed based on the national fuel type classification (FTC) system [35]. The FTC system was designed with two main groups of fuels, surface and crown fire-carrying fuels. The principal fire-carrying surface fuels consist of five categories of conifer fuels (*Pinus densiflora forma erecta* Uyeki, *Pinus densiflora* Siebold & Zucc. for central southern lowland and upland ecotypes, *Pinus rigida* Mill., *Pinus koraiensis* Siebold & Zucc., and *Pinus thunbergii* Parl.) and one common broadleaf fuel with respect to 6 classes of tree age groups. The crown fire-carrying fuels are only considered to be conifer species (*P. densiflora*, *P. rigida*, *P. koraiensis*, *P. thunbergii*, and *Larix kaempferi* (Lamb.) Carr.) (Figure 2 and Tables S1 and S2). Once the fire area is determined from the fire spread model, fuel loadings are automatically estimated for surface and crown-fire phases, respectively.



**Figure 2.** Distribution of (a) surface- and (b) crown-fire carrying fuels ( $\text{kg}/\text{m}^2$ ) in Korea.

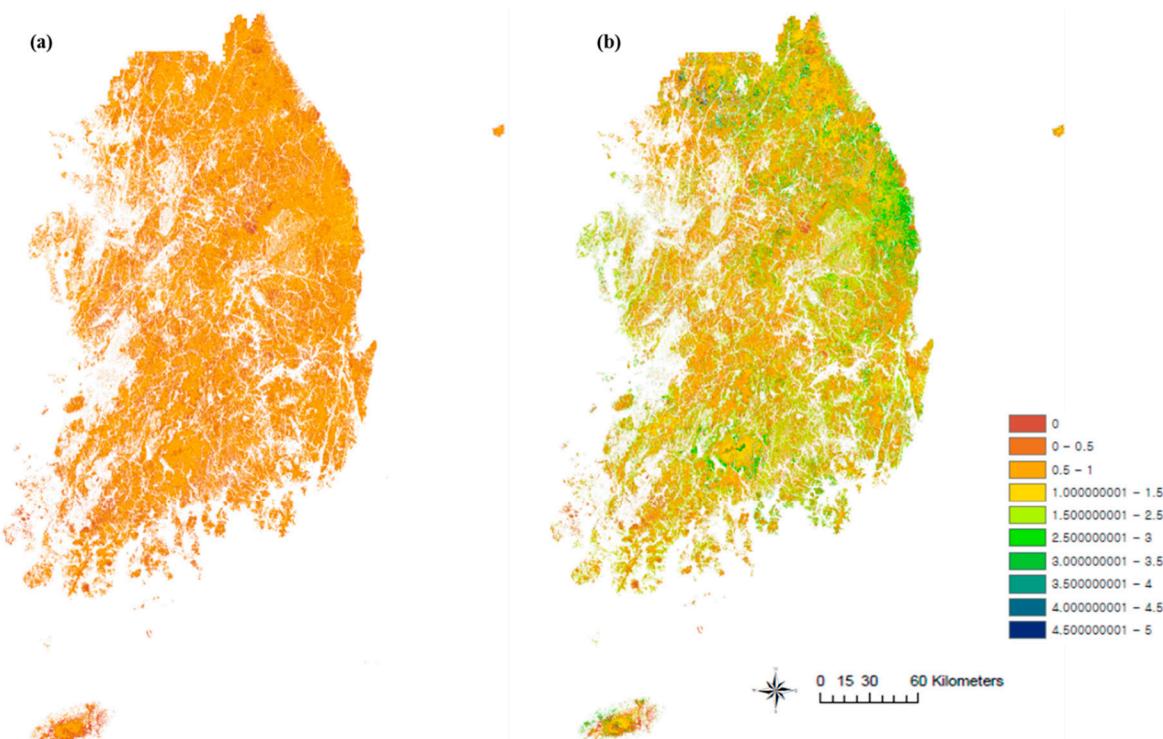
## 2.3. Fuel Consumption

Once fire location, size, and fuel loadings are known, the amount and type of fire consumption for every unit area burned can be processed. In the KFSDP system, the total fire consumption was determined by two stages of fire-consumption events: surface and crown-fire consumptions. At each stage, fuel consumption was estimated by multiplying the amount of fuel loadings for each cell passed from the module of fuel loading by a value of combustion efficiency (Figure 1). Within the KFSDP system, the combustion efficiency was provided for surface and crown fires with respect to conifer and broadleaf fuels, respectively (Table 1). These values were estimated based on the residual stump measurements of fuel combustion in forest fires that had occurred across Korea [35]. Here, the broadleaf fuels were considered to only be involved in surface fires. The estimated fuel consumptions for surface

and crown fires were then generated as the GIS layers for each cell (Figure 3), which were used as input information to quantify the emission estimates in the next module.

**Table 1.** Combustion efficiency for surface- and crown-fire carrying fuels.

	Conifer Fuels		Broadleaf Fuels	
	Surface Layer	Crown Layer	Surface Layer	Crown Layer
Surface fire	54%	-	62%	-
Crown fire	76%	89%	-	-



**Figure 3.** Distribution of (a) surface and (b) crown fuel consumption ( $\text{kg}/\text{m}^2$ ) in Korea.

#### 2.4. Emission Production Module (EPM)

Emissions from forest fires were estimated by multiplying total fuel consumption by emission factors of each compound ( $\text{CO}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_{10}$ ) (Figure 1). As forest fires are categorized as surface and crown fires in the KFSDP system, emission factors were also required for each fire type with regard to  $\text{CO}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_{10}$ . The emission factors were derived for each pollutant compound based on the concentrations measured from combustion products using conifer and broadleaf fuels in the laboratory [36] and a carbon mass balance model [37]. First, combustion experiments were implemented to measure the concentrations of each compound for each type of fire. For surface fires, the dead leaves of *P. densiflora* and *Quercus variabilis* Blume, which are considered to be representative species of conifer and broadleaf fuels, were combusted to sample each compound. For crown fires, the dead leaves, live leaves, and branches of *P. densiflora* were burned to sample smoke compounds since crown fires mainly involved conifer fuels when surface and crown fires occurred at the same time (Table 2). Then, emission factors were estimated for each compound using a carbon mass balance technique (Table 2) wherein  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  were assumed to be composed of 60% carbon and the fuel carbon fraction was considered to be 50% [38]. Once the total fuel consumption of GIS grids was determined for forest fire areas at 30-min intervals in the fuel consumption module, the amounts of emission were automatically calculated for each smoke compound ( $\text{CO}$ ,  $\text{PM}_{2.5}$ , and  $\text{PM}_{10}$ ) based on emission factors supplied in the KFSDP system.

**Table 2.** Emission factors for smoke pollutants of CO, PM<sub>2.5</sub>, and PM<sub>10</sub>.

Fuel Type	Fire Type	Vegetation Type	Measured Emission Factors			Estimated Emission Factors		
			CO ppm	PM <sub>2.5</sub> * µg/m <sup>3</sup>	PM <sub>10</sub> ** µg/m <sup>3</sup>	CO g/kg	PM <sub>2.5</sub> g/kg	PM <sub>10</sub> g/kg
Conifer fuels	Surface fire	Pine leaves	27.30	4458.10	5232.80	32.50	4.60	5.39
	Crown fire	Pine dead/live leaves and needles	34.20	16,444.30	20,785.60	49.00	20.50	25.94
Broadleaf fuels	Surface fire	Oriental oak dead leaves	22.60	7326.00	7962.00	28.80	8.10	8.90

\* PM<sub>2.5</sub> is fine (<2.5 µm) particulate matter. \*\* PM<sub>10</sub> is coarse (<10 µm) particulate matter.

## 2.5. Smoke Dispersion Module

Since 98.5% of forest fires that have been recorded in Korea have been smaller than 10 ha, wherein the smoke appeared to disperse less than 50 km along the downwind distance based on satellite imagery of smoke dispersion [18,31], a GPDM was adopted to forecast smoke dispersion in the KFSDP system [39]. The smoke concentration in a GPDM is represented by a Gaussian distribution in the direction of a constant wind [40] as follows:

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \left[ \exp - \left( \frac{y^2}{2\sigma_y^2} \right) \right] \left\{ \exp \left[ \frac{-(z-H)^2}{2\sigma_z^2} \right] + \exp \left[ \frac{-(z+H)^2}{2\sigma_z^2} \right] \right\} \quad (1)$$

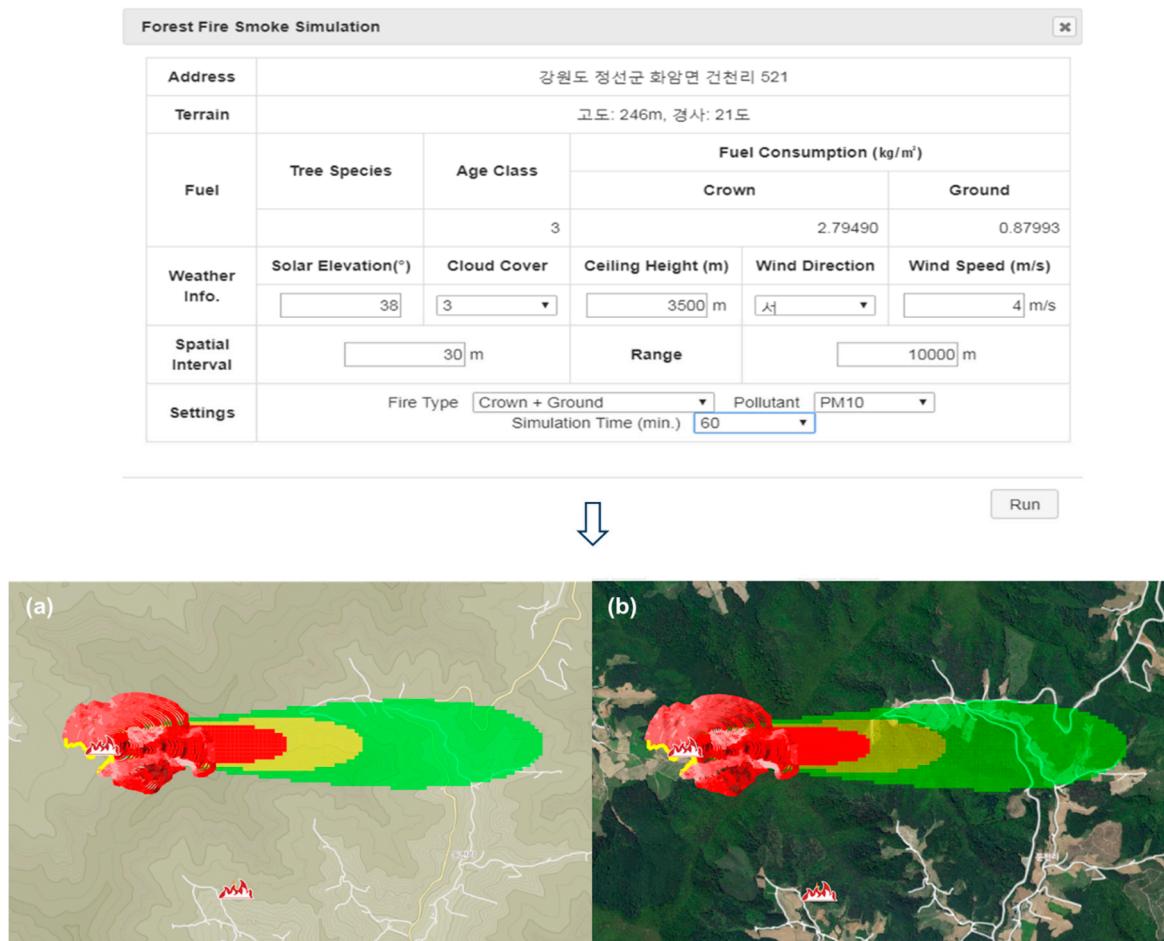
where  $C(x, y, z)$  is a smoke concentration (g/m<sup>3</sup>) at downwind ( $x$ ), horizontal ( $y$ ), and vertical ( $z$ ) positions,  $Q$  is an emission rate of fire smoke (g/s),  $u$  is a wind speed at the fire smoke emission height (m/s),  $\sigma_y$  and  $\sigma_z$  are horizontal ( $y$ ) and vertical ( $z$ ) dispersion coefficients (m), and  $H$  is a height at the fire smoke emission point (m).

In the KFSDP system, the GPDM is designed to assess the ground-level smoke concentrations of CO, PM<sub>2.5</sub>, and PM<sub>10</sub> for downwind distances up to a specified distance, such as 10 km. The dispersion coefficients in the GPDM are determined as the function of the distance from an emission source and a Pasquill atmospheric stability classification (PASC) system [41]. The PASC is divided into six descriptive classes, which are determined based on surface wind speeds and insolation in the day or cloud cover at night. Figure S1 presents a flowchart for an algorithm used to determine a Pasquill atmospheric stability class for the further determination of dispersion coefficients processed in the KFSDP system. Weather information, including wind speeds and directions, is automatically provided within the algorithm via an open application program interface (API) of the Korea Meteorological Administration (<http://data.go.kr>) wherein hourly, numerical weather predictions are generated by the KWRF model [42]. However, the data of cloud cover and ceiling height were supplied manually via the graphical user interface (GUI) in the GPDM system (Figure 4). Once the atmospheric stability is specified, the values of dispersion coefficients are automatically generated by the Caraway equation, relating the dispersion coefficients with the distance through indices. The mixing height of smoke emissions in the GPDM was defined as a tree height plus 2 m. The wind speed generated from the KWRF model was adjusted to the wind speed at the mixing height through the following equation, and was then used in the GPDM:

$$U_z = U_0 (Z/Z_0)^P \quad (2)$$

where  $U_z$  is an adjusted wind speed at a mixing height (m/s),  $U_0$  is a wind speed at a physical source height (m/s),  $Z$  is a height of smoke in a vertical direction (m),  $Z_0$  is a height where an anemometer is located (m), and  $P$  is the Pasquill stability class.

Once emission estimates from EPM were processed and model parameters such as meteorological information and a spatial range for a simulation output were entered by users in the GUI of the GPDM (Figure 4), the GPDM in the KFSDP system was finally implemented to simulate the ground-level emission concentrations of CO, PM<sub>2.5</sub>, and PM<sub>10</sub>. The pollutant concentration results were then displayed as a color-coded smoke dispersion contour according to the Comprehensive Air quality Index (CAI) to describe ambient air quality accounting for forest fire smoke (Figure 4).



**Figure 4.** Graphical user interface (GUI) of Gaussian smoke dispersion model and smoke prediction output enabled by the Korean forest fire smoke dispersion prediction (KFSDP) framework. The forest fire was simulated in Jeongseon, Kwangwon-do, Korea simulated from 7:30 a.m. to 4:30 p.m. on April 11, 2018. Both fires and predicted dispersion of PM<sub>10</sub> concentrations are shown. Users can animate the forecasts, zoom, pan, and map data in both (a) Keyhole Markup Language (KML) and (b) satellite layers. PM<sub>10</sub> is coarse (<10  $\mu\text{m}$ ) particulate matter.

The CAI is a Korean air quality index used to describe ambient air quality based on the health risks associated with air pollution. The CAI helps the public to easily understand air quality levels, and it protects human health from air pollution [43]. The CAI has values ranging from 0 through 500, which are divided into four categories (Good, Moderate, Unhealthy, and Very unhealthy) denoted by four different colors. The higher the CAI value, the greater the level of air pollution (Table 3). In the KFSDP system, the GPDM results were represented by each color overlay of the expected downwind ground-level CO (1-h mean value) and PM<sub>2.5</sub> and PM<sub>10</sub> (24-h mean value) concentration contours that reflect the threshold values (i.e., for the categories of Moderate, Unhealthy, and Very unhealthy) of the CAI to indicate possible areas of hazardous smoke impacts.

**Table 3.** Description of the comprehensive air quality index (CAI).

CO 1 h-Average (ppm)	PM <sub>10</sub> 24 h-Average ( $\mu\text{g}/\text{m}^3$ )	PM <sub>2.5</sub> 24 h-Average ( $\mu\text{g}/\text{m}^3$ )	Category	CAI	Level of Health Concern	Health Effects
0–2	0–30	0–15	A	0–50	Good	A level that will not impact patients suffering from diseases related to air pollution.
2.01–9	31–80	16–35	B	51–100	Moderate	A level that may have a slight impact on patients in cases of chronic exposure.
9.01–15	81–150	36–75	C	101–250	Unhealthy	A level that may have harmful impacts on patients and members of sensitive groups (children, aged, or sick people), and also cause the general public irritation.
15.01–30	151–300	Greater than 76	D	Greater than 251	Very unhealthy	A level which may have serious impacts on patients and members of sensitive groups in cases of acute exposure.
30.01–50	301–600		E			A level which may necessitate emergency measures for patients and members of sensitive groups and have harmful impacts on the public.

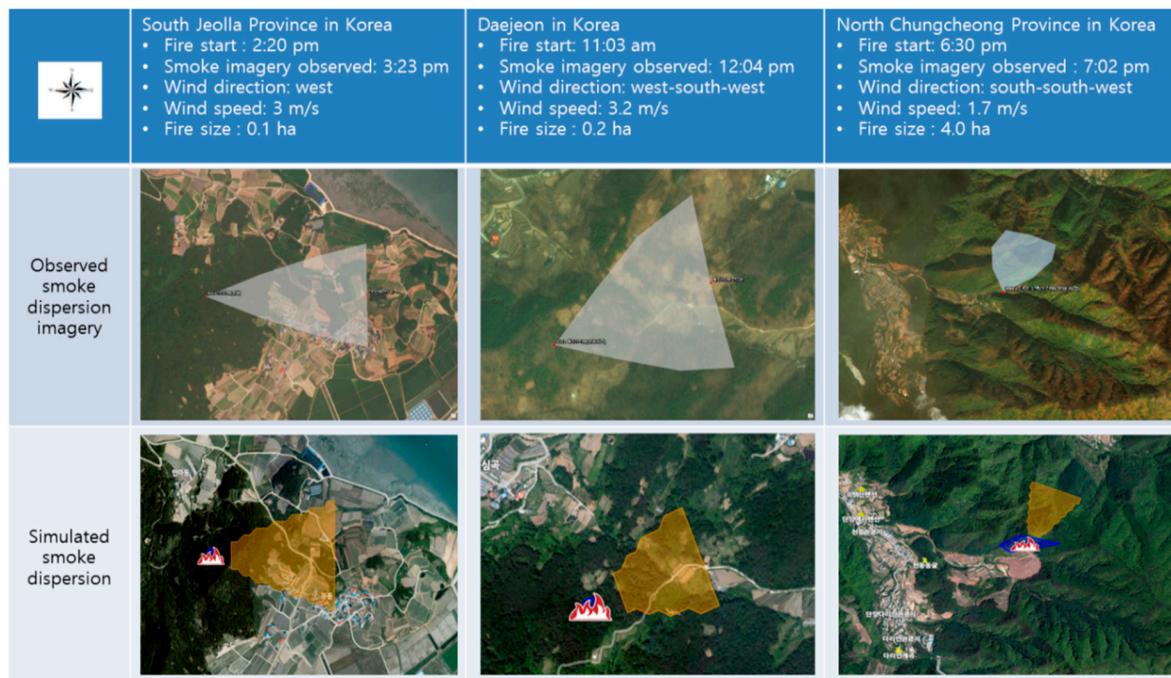
\* PM<sub>10</sub> is coarse (<10  $\mu\text{m}$ ) particulate matter. \*\* PM<sub>2.5</sub> is fine (<2.5  $\mu\text{m}$ ) particulate matter.

### 3. Results and Discussion

The capabilities of the KFSDP system were examined by comparing the dispersions of simulated smoke plumes with smoke plumes observed from real forest fires. Additionally, the dispersions of smoke plumes in the context of CO, PM<sub>2.5</sub>, and PM<sub>10</sub> concentration contours based on “what-if” model scenarios for defined forest fires were forecasted. For “what-if” model scenarios, simulated fires were assumed to take place from 7:30 a.m. to 4:30 p.m. on April 11, 2018 in Jeongseon, Kwangwon-do, Korea on the basis of a 30-m  $\times$  30-m spatial grid (Figure 4).

#### 3.1. Evaluation of Smoke Plume Dispersion

Validation of the KFSDP system was undertaken by comparing modeled smoke plumes with three observed smoke plumes captured from actual forest fires that occurred in Korea. There were no data for smoke plume concentrations, only images of smoke plume dispersions from actual fires. The images were recorded from a firefighting helicopter during fires and processed to extract the shape of smoke plume dispersions onto a Google Earth map (Figure S2). Since we only had the extracted imagery data for the observed plumes, the smoke plumes were simulated as total smoke concentrations in the KFSDP system based on monitored forest fire information, and compared with observed images of smoke plume dispersions projected using Google Earth. Model performance was evaluated with respect to the overall plume shape and range of transport. Three simulated smoke plumes showed outlined areas that overlapped relatively well with the observed smoke plumes, except for the area of smoke plume dispersion that occurred in Daejeon, Korea (Figure 5). Overall, the good performance of simulated results indicates that the KFSDP system is a suitable tool for predicting the dispersion of smoke plumes from forest fires in Korea.

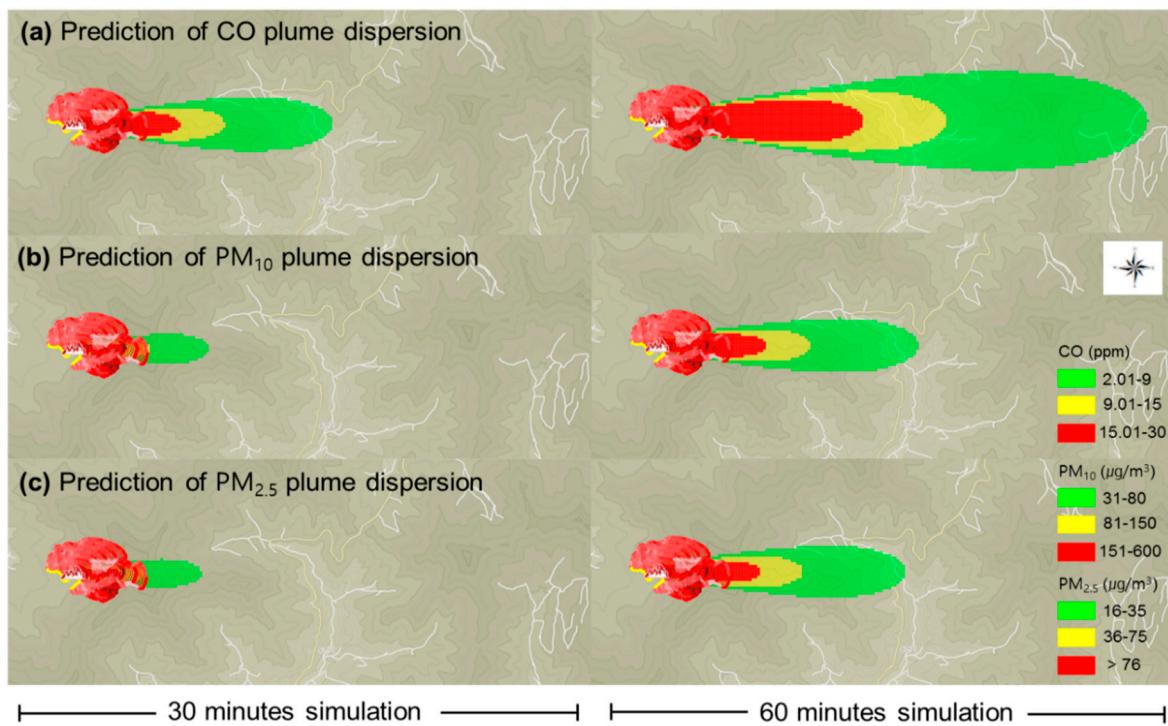


**Figure 5.** Comparison of smoke dispersion predictions with observed surface smoke plumes from real forest fires in Korea.

### 3.2. Characteristics of CO, PM<sub>10</sub>, and PM<sub>2.5</sub> Plume Dispersions

The KFSDP system was employed to verify the characteristics of smoke plume dispersions with respect to CO, PM<sub>10</sub>, and PM<sub>2.5</sub> concentration contours using “what-if” model scenarios. As a real-time model simulation, the dispersions of CO, PM<sub>10</sub>, and PM<sub>2.5</sub> plume contours were simulated for two time intervals (30 min and 60 min). Given the 30-min and 60-min simulated outputs of 2400-m<sup>2</sup> and 5000-m<sup>2</sup> fire areas, “what-if” weather conditions with a solar elevation of 38°, cloud cover of 3, ceiling height of 3500 m, and a west wind of 4 m/s were assigned.

Figure 6 displays the spatial and temporal distributions of 1-h averaged CO and 24-h averaged PM<sub>10</sub> and PM<sub>2.5</sub> plume concentration contours with the entire fire area burned. In general, the CO plume appeared more diffused relative to the PM<sub>10</sub> and PM<sub>2.5</sub> plumes (Figure 6a). The pattern of PM<sub>10</sub> and PM<sub>2.5</sub> plume dispersions showed a minor difference (Figure 6b,c). As time progressed from 30 min to 60 min, the magnitude and location of each pollutant plume dispersion appeared to be more dispersed regardless of the pollutant type due to the increased size of the burned area. It is worth noting that the KFSDP system performs an automated retrieval of fire areas burned for a respective time interval simulation of smoke plume dispersion, and displays only the simulated result of a smoke plume contour with the entire fire area burned (Figure 6).



**Figure 6.** Predicted dispersions of (a) CO, (b) PM<sub>10</sub>, and (c) PM<sub>2.5</sub> plume concentration contours after 30 min and 60 min of smoke simulations. Both fires and predicted CO, PM<sub>10</sub>, and PM<sub>2.5</sub> surface concentrations are shown. PM<sub>2.5</sub> and PM<sub>10</sub> are fine ( $<2.5\text{ }\mu\text{m}$ ) and coarse ( $<10\text{ }\mu\text{m}$ ) particulate matter, respectively.

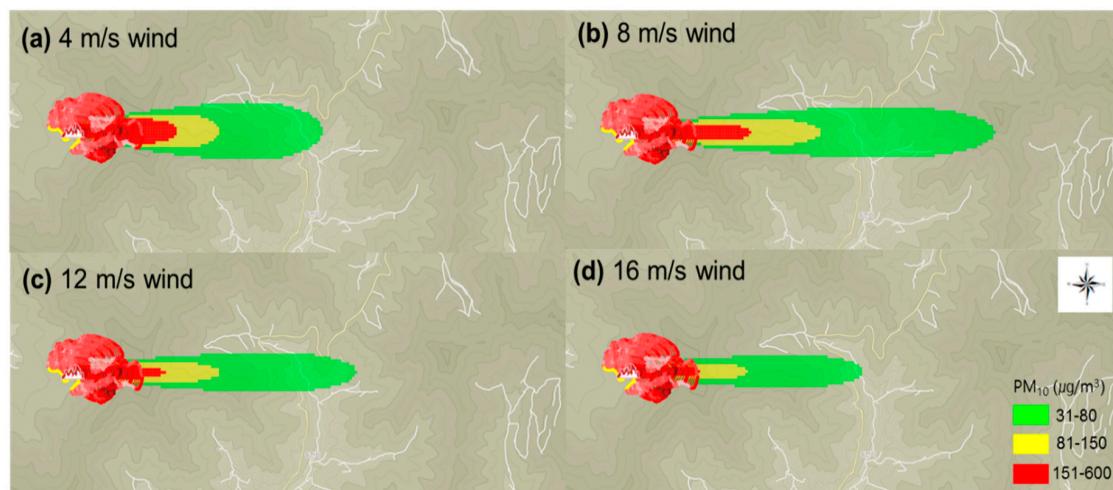
Overall, the results of the simulated scenarios demonstrate the capability of the KFDSP system to produce real-time predictions of smoke transport in terms of CO, PM<sub>10</sub>, and PM<sub>2.5</sub> concentrations given fire activity and weather. This indicates that the KFDSP system could be used as a screening model for a quick evacuation from the hazardous smoke of forest fires [44,45]. Particularly, it also implies that the capability of the real-time forecasting mode of the KFDSP system can effectively improve the accuracy of smoke plume dispersion predictions since a Gaussian plume model can only deal with a static dispersion, such as VSMOKE [46] and the Simple Approach Smoke Estimation Model (SASEM) [47].

### 3.3. Effects of Wind Speed and Direction on Smoke Plume Dispersion

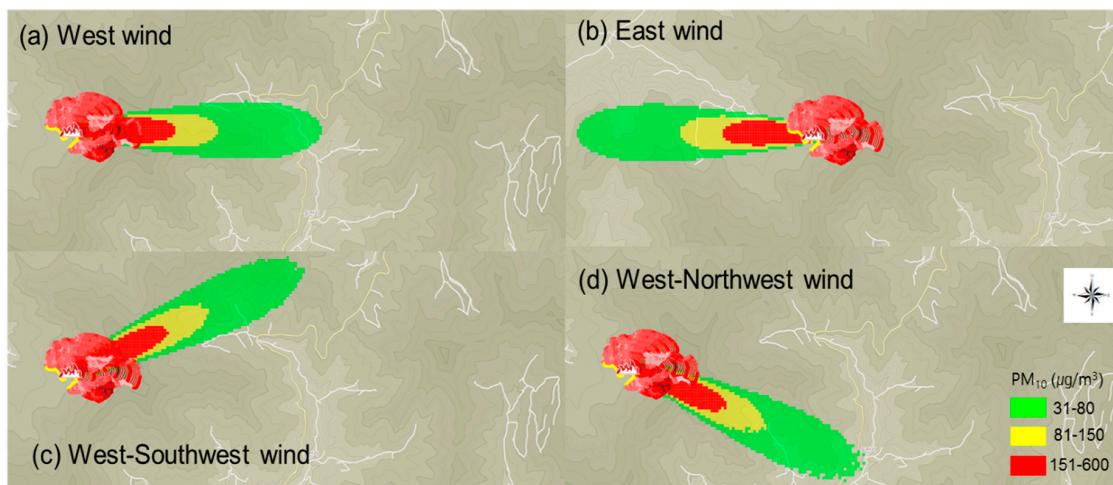
The effects of wind speed and direction on smoke plume dispersion were examined by simulating “what-if” scenarios under four different wind speeds and directions (Figures 7 and 8). In each simulation, the dispersion of smoke plume concentrations was assessed in terms of a PM<sub>10</sub> plume concentration contour for the 60-min simulated output of the fire area burned ( $5000\text{ m}^2$ ). To analyze the scenario, the meteorological conditions specified were a solar elevation of  $38^\circ$ , cloud cover of 3, and a ceiling height of 3500 m. The “what-if” analysis for the effect of a wind direction was performed under a wind speed of 4 m/s.

The model simulations demonstrate that the dispersion of a PM<sub>10</sub> plume concentration varied significantly by wind speed (Figure 7). The spread of the PM<sub>10</sub> plume contour appeared to be the largest at 8 m/s wind speed and was relatively narrower and shorter under higher wind speeds. This variation could be attributed to the changing stability of atmospheric conditions along with wind speeds. It also indicates that the dispersion of a PM<sub>10</sub> plume concentration is disproportional with wind speed under the same atmospheric conditions where the model scenarios correspond to near neutral conditions above 8 m/s wind speeds given specified “what-if” weather conditions (Figure 7b-d). With regard to the effects of wind direction, simulations showed that the direction of a PM<sub>10</sub> plume dispersion was significantly dependent on wind direction (Figure 8).

Overall, the results of model simulations indicate that the 30-min forecasting mode in the KFDSP system can be used to capture the variability of wind speed and direction on smoke plume dispersion for real emission scenarios. This correspondingly implies that a time-varying function of wind speed and direction can reduce the limitations of a steady-state distribution using the Gaussian plume model in the KFDSP system. This is also an important step forward relative to current smoke dispersion systems, such as the BlueSky Playground beta, which can only simulate smoke dispersion under a constant wind speed and direction [48].



**Figure 7.** Comparison of the effects of wind speeds on predicted dispersions of  $\text{PM}_{10}$  plume concentration contours: (a) 4 m/s winds, (b) 8 m/s winds, (c) 12 m/s winds, and (d) 16 m/s winds. Both fires and predicted  $\text{PM}_{10}$  surface concentrations are shown.  $\text{PM}_{10}$  is coarse ( $<10 \mu\text{m}$ ) particulate matter.



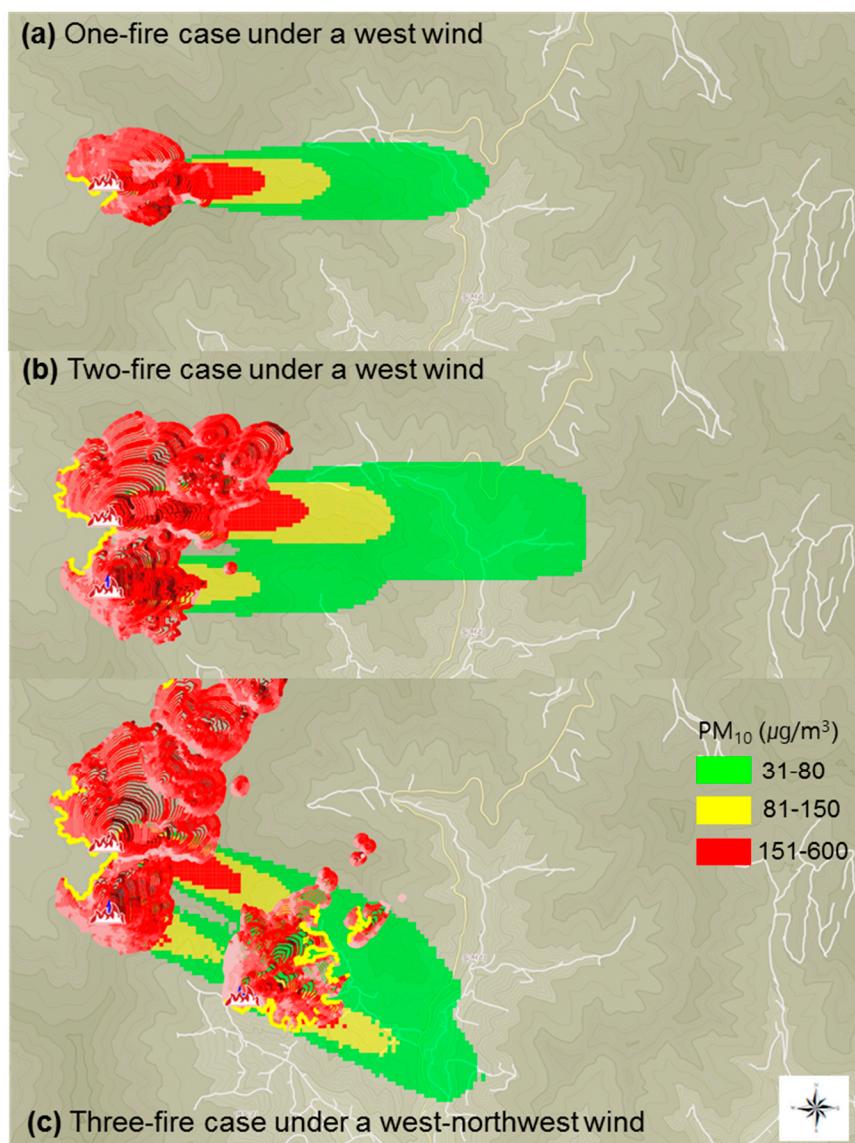
**Figure 8.** Comparison of the effects of wind directions on predicted dispersions of  $\text{PM}_{10}$  plume concentration contours: (a) west winds, (b) east winds, (c) west-southwest winds, and (d) west-northwest winds. Both fires and predicted  $\text{PM}_{10}$  surface concentrations are shown.  $\text{PM}_{10}$  is coarse ( $<10 \mu\text{m}$ ) particulate matter.

### 3.4. Effects of Multiple Fires on Smoke Plume Dispersion

The effects of smoke plume dispersion from multiple fires were examined by three fire scenario simulations. In each simulation, the dispersion of smoke plume concentrations was assessed in terms of a  $\text{PM}_{10}$  plume concentration contour from the 60-min simulated outputs of three fire events, with areas of  $5000 \text{ m}^2$  (first fire),  $6000 \text{ m}^2$  (first and second fires), and  $7800 \text{ m}^2$  (first, second, and third fires). To analyze the scenario, the meteorological conditions was specified as a solar elevation of  $38^\circ$ , cloud

cover of 3, and a ceiling height of 3500 m under west and west-northwest wind directions at a speed of 4 m/s.

Figure 9 displays the superimposed dispersion of  $\text{PM}_{10}$  plume concentration contours from multiple fires. The three-fire scenario shows substantially larger dispersion of  $\text{PM}_{10}$  plume ground-level concentrations than the one-fire scenario. In particular, the multiple fire scenario contributed to an increase in the spreading of moderate levels of  $\text{PM}_{10}$  concentrations due to the cumulative effects of plume concentrations from multiple fires (Figure 9b,c). Overall, model simulations demonstrate that the KFDSP system can effectively facilitate forecasting the combined effects of smoke plume dispersions from multiple fire sources. This correspondingly indicates that the KFDSP system shows a substantial improvement over current smoke dispersion systems, such as a BlueSky Playground beta, which can only simulate smoke dispersion for a one-fire event [48].



**Figure 9.** Effects of multiple fires on predicted dispersions of  $\text{PM}_{10}$  plume concentration contours: (a) one-fire scenario under a west wind, (b) two-fire scenario under a west wind, and (c) three-fire case under a west-northwest wind. Both fires and predicted  $\text{PM}_{10}$  surface concentrations are shown.  $\text{PM}_{10}$  is coarse ( $<10 \mu\text{m}$ ) particulate matter.

#### 4. Conclusions

The KFSDP system, a real-time smoke dispersion forecast system for forest fires, was developed for the first time to assist with smoke management efforts in Korea. It is designed to be a decision-support tool for an early warning system to evacuate communities quickly from areas of exposure to hazardous smoke from forest fires across Korea. The KFSDP system is operated by an integrated modeling system consisting of a fire growth spread model, grid-based GIS fuel loading and consumption maps, the KWRF model, and a Gaussian plume model sequentially linked to simulate the ground-level plume concentrations of smoke dispersion.

The capability of the KFSDP system was demonstrated through the evaluation of its performance by comparing simulated smoke plumes with measurements from real forest fires and by analyzing “what-if” scenarios. The smoke plumes modeled using the KFSDP system generally compared well with plume observation images captured from a firefighting helicopter with respect to the overall plume shape and range of transport. In “what-if” scenario analyses, the KFSDP system demonstrated the potential to forecast varied smoke plume dispersions in real-time based on automated estimations of fuel consumption and forecasted meteorology for a specified forest fire.

These analyses also showed that the KFSDP system is capable of proper predictions of smoke dispersion under various wind speed and direction conditions and for multiple-fire scenarios. These results demonstrate that the KFSDP system provides an effective means of predicting smoke plume dispersion as an early warning system to inform and reduce human exposure to hazardous smoke from forest fires across Korea.

To further assess the robustness of the KFSDP system, model scenarios may be tested using future sampling data. Future research on the determination of plume rise for a better description of plume structure will also improve the accuracy of smoke dispersion prediction. Moreover, the incorporation of the effects of rough terrains on dispersion coefficients, reflecting the geography of mountainous forests in Korea, will further enhance the accuracy of smoke dispersion prediction.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/1999-4907/10/3/219/s1>, Figure S1: Algorithm for determining the dispersion coefficients using Pasquill atmospheric stability classes and the Caraway dispersion equation, Figure S2: Generation of the shape of observed smoke plume dispersion, Table S1: Surface fire-carrying fuel loadings, Table S2: Crown fire-carrying fuel loadings.

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