



Article Wildfire Smoke Transport and Air Quality Impacts in Different Regions of China

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Abstract: The air quality and human health impacts of wildfires depend on fire, meteorology, and demography. These properties vary substantially from one region to another in China. This study compared smoke from more than a dozen wildfires in Northeast, North, and Southwest China to understand the regional differences in smoke transport and the air quality and human health impacts. Smoke was simulated using the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) with fire emissions obtained from the Global Fire Emission Database (GFED). Although the simulated PM_{25} concentrations reached unhealthy or more severe levels at regional scale for some largest fires in Northeast China, smoke from only one fire was transported to densely populated areas (population density greater than 100 people/km²). In comparison, the PM_{2.5} concentrations reached unhealthy level in local densely populated areas for a few fires in North and Southwest China, though they were very low at regional scale. Thus, individual fires with very large sizes in Northeast China had a large amount of emissions but with a small chance to affect air quality in densely populated areas, while those in North and Southwest China had a small amount of emissions but with a certain chance to affect local densely populated areas. The results suggest that the fire and air quality management should focus on the regional air quality and human health impacts of very large fires under southward/southeastward winds toward densely populated areas in Northeast China and local air pollution near fire sites in North and Southwest China.

Keywords: wildfire; PM2.5 emission; smoke modeling; HYSPLIT; local and regional impacts

1. Introduction

Wildfires have increased in many regions of the world with a large number of devastating wildfires in recent years [1–7]. About two dozen extremely large fires occurred in the western United States in 2017 and 2018 with totally burned areas of about 22 thousand km² (2.3 million hectares (hm²)). The 2018 Camp Fire in northern California damaged nearly 19 thousand structures and led to 85 deaths. The 2019–20 Australia bushfires burned 160 thousand km² (16 million hm²) lands, leading to losses of over 3000 houses and 33 lives. The 2019 Amazon fires burned about 1500 km² (150 thousand hm²) rainforest. The 2017 Portugal fires burned 5000 km² (0.5 million hm²) with a loss of 119 human lives and the 2018 Greece Mati fires caused a loss of 99 people. In Russia, 25 thousand km² (2.5 million hm²) were burned in 2019. Analyses and simulations have been conducted to understand fire occurrence and spread, weather and climate conditions, and the impacts of these fires.

Forest fires are an important source of air pollutants. Fires occur and re-occur on almost a third of the global landmass at different return intervals, with burned areas averaging 4.5 million km² annually [8,9]. Fires emit a large amount of gases including CO₂, CO, CH₄ and fine particular particles with a diameter of 2.5 micrometers or smaller (PM_{2.5}). Although fine particles only account for 1.8% of flue gas [10], they can seriously affect air quality and human health [11–15]. Fine particles from fires not only affect local air quality, but also can be lifted to high altitudes by the heat of combustion and transported a long distance downwind to affect regional air quality and climate [16]. The contributions of fire emissions to air pollutants have been assessed in many regions of the world. For example, fires were found to contribute to about 30% of total PM_{2.5} emissions in the United States [17].

China is one of the most polluted countries in the world [18]. Average $PM_{2.5}$ concentrations are over 50 µg/m³ in most of eastern China and even over 100 µg/m³ in some areas of this region [19]. Fine particles are also a key factor for the formation of regional haze and smog [20]. The severe pollutions cause premature deaths of more than one million people each year in China [21]. China has categorized local air pollution sources from automobile, industry, residence heating, and construction in major cities [22]. However, it is still not clear about the contributions from outside sources including wildfires [23].

The air quality and human health impacts of wildfires depend on many factors. Fire emission is a most important factor. Wildfires in China occur mainly in eastern China (approximately east of 110° E). Northeast and Southwest China are the two major fire regions with opposite contributions to the total number of fires and burned areas in China [24]. Northeast China has less than 5% of the total number of fires in China, but about 60% of the total burned areas; in contrast, Southwest China accounts for about 25% of the total number of fires, but only about 10% of the total burned areas [25]. Thus, it is expected that air pollutant emissions of individual fires are larger but occur less frequently in Northeast than in Southwest China. The contributions of fires in other regions to the total number of fires and burned areas in China are in between those in Northeast and Southwest China.

Meteorological conditions are another important factor. Besides local temperature, humidity, wind, and precipitation that affect fire occurrence, spread, and smoke plume rise, large-scale circulations control long-distance transport of smoke [26]. All regions in China except the Northeast have a fire season mainly in spring. Although Northeast China has a fire season with two periods of spring and fall, fires in spring account for more than 70% of the total annual fires [25]. Thus, atmospheric circulations in spring are critical for smoke transport. Eastern China is mainly under the control of the winter phase of the East Asian monsoon [27] during the spring. The prevailing circulation system during this season is westerly in the mid-latitudes with dominant airflows from west to east.

Demography is another factor for the air quality and human health impacts of wildfire smoke. The smoke exposure rate is closely related to population density. The rural population density is mostly between 10 and 100/km² in eastern China, about 100–400/km² in about one third of this region, including southern Northeast China, southeastern North China, and northeastern Southwest China [28]. The location of populated areas relative to the fire sites are critical to smoke exposure. Fires in Northeast China occur mainly in the Daxing'anling Mountains by the China-Russia border in far northwest of this region. The highly populated areas are located south of the fire sites and therefore not downwind of the prevailing westerly winds. In contrast, fires in the Southwest occur mostly in the western mountains with highly populated areas located downwind of the prevailing westerly winds. The locations of highly populated areas in North China are similar to those in Southwest China.

Wildfire research in China has focused on fire ecology, fire-climate relationships, and fire prevention and suppression [29,30]. There have been increasing research efforts in fire emissions [31,32]. However, the studies on smoke transport and the air quality impacts are largely absent. This study investigated this issue with a focus on the regional differences. A hypothesis for this study was that individual fires in Northeast China have had large emission but small chance to affect air quality in highly populated areas, but an opposite situation might have happened for fires in Southwest and North China. This study is expected to be valuable for evaluating the contributions of wildfires to air pollutions and improving fire and air quality management in China.

2. Methodology

2.1. Study Area

The study area was in eastern China, which was divided into five regions (Figure 1). The fire cases investigated in this study were from the Northeast, North, and Southwest China regions. China has a three-step topography with generally increasing elevations from east to west (Figure 1a). The step 1 topography consists of the coastal plains and hills mostly below 500 m. The step 2 topography consists of the mountain ranges up to 3000 m (expect a lower area called the Sichuan Basin in northern Southwest China). The step 3 topography consists of the Tibet Plateau of 3000–6000 m and the northwestern deserts and mountains of 1000–3000 m. The eastern Northeast and North China are within the step 1 topography; the Southwest, western Northeast, and western North China are within the step 2 topography, where a majority of lands are covered by needle and broad leaf trees (Figure 1b). The population density distributions described in the introduction section are illustrated in Figure 2a. The population density was classified as sparsely (<10 people/km²), moderately (10–100 people/km²), and densely (>100 people/km²) populated in this study. The three classifications approximately accounted for 60, 30, and 10% areas of the Northeast region, one third each of the North region, and 20, 60, and 20% of the Southwest region.



(a)

Figure 1. Cont.



(b)

Figure 1. Elevation (**a**) and land cover (**b**) in China with geographic regions in eastern China and fire locations (The data used to produce this figure were from [33]).



(a)

Figure 2. Cont.



Figure 2. Population density (**a**) (from [28]) and atmospheric circulation in the 500 hPa geopotential height field; (**b**) (drawn using the data from the US National Centers for Environmental Prediction/Department of Energy Reanalysis-2 [34]).

Northeast, North, and Southwest China are under the control of the East Asian monsoon, which is extremely wet and warm during the summer phase and dry and cold during the winter phase. Southwest China is also affected by the South Asian monsoon, which includes wet and dry phases. Fires in the three regions occurred mainly during the East Asian winter/South Asia dry monsoon phase. The spring 500 hPa geopotential height (Figure 2b) shows the westerly zone north of about 25° N with a trough located east of China and a ridge over western China and Mongolia. The corresponding prevailing airflows over the Northeast, North, and Southwest China are mainly westerly (i.e., eastward), as indicated by the arrows. The ground airflows are more complex due to the impacts of topography and weather systems such as fronts.

2.2. Fire Cases

A total of 16 fires were investigated, seven from the Northeast, six from the North, and three from the Southwest region (Figure 1 and Table 1). Four fires each in the Northeast and North regions occurred in the step 1 topography and the rest of the fires occurred in the step 2 topography. Thirteen fires occurred in spring, two in fall, and one in summer. The burned areas in the Northeast region were over 1000 km² (100 k hm²) for three fires, 100–1000 km² (10–100 k hm²) for two fires, and 50–100 km² (5–10 k hm²) for two fires. The durations were longer than a week for five fires and four days for two fires. The fires in the North and Southwest regions had burned areas of over 10 km² (1 k hm²) for four fires and 1–10 km² (0.1–1 k hm²) for five fires. The durations were longer than a week for two fires and 2–6 days for seven fires. The annual fire numbers during 1999–2017 were about 350, 230, 1850, and 7080 in the Northeast, North, and Southwest regions and in entire China based on the data from the China National Forestry and Grassland Administration's China National Forest Fire Statistical System [35]. The corresponding burned areas were about 1190, 210, 240, and 2110 km² (119, 21, 24, and 211 k hm²). The averaging burned areas were about 3.5, 0.9, 0.13, and 0.3 km² (350, 90, 13, and 30 hm²) each fire. The examples from the Northeast regions were also larger than their averaging size.

Region	No.	Name	Location		D · 1		CEED Frank Trans
			Lon(° E)	Lat(° N)	Period	Burned Area (km²)	GFED Fuel Type
Northeast	1	Shibazhan	125.78	52.10	5/17-26, 2003	3192.53	Boreal forest
	2	Wuerqihan	122.66	49.54	5/25-6/1,2006	299.56	Boreal forest
	3	Huzhong	122.83	51.41	6/26-7/3,2010	95.75	Boreal forest
	4	Yichun	129.81	49.26	10/3–6, 2007	175.70	Boreal forest
	5	Huma	126.55	51.13	10/23–30, 2005	1087.30	Boreal forest
	6	Songling	124.63	50.88	5/22-6/2,2006	2211.29	Boreal forest
	7	Yimuhe	120.49	53.03	5/31-6/3,2006	60.06	Boreal forest
North -	8	Baoding	114.39	39.30	4/6-8,2014	4.50	Temperate forest
	9	Yangquan	113.46	37.90	4/29–5/1, 2011	22.49	Temperate forest
	10	Weihai	122.12	37.49	5/29-31, 2014	1.20	Temperate forest
	11	Funing	119.63	40.13	4/12–18, 2011	10.67	Temperate forest
	12	Laiwu	117.93	36.62	4/16–19, 2011	3.08	Temperate forest
	13	Jinan	116.19	35.98	4/18–20, 2011	4.58	Temperate forest
Southwest	14	Chuxiong	102.04	25.22	4/23–28, 2013	10.13	Temperate forest
	15	Anning	102.68	25.06	3/29-4/7, 2006	18.49	Temperate forest
	16	Dali	100.32	25.70	3/8–9, 2007	2.52	Temperate forest

Table 1. Fire cases for smoke modeling.

Fire boundaries, which were not available from the fire information provided by the fire management agency of China, were obtained from the Fire Information for Resource Management System (FIRMS) [36]. The FIRMS products had a resolution of 0.25° (approximately 25 km), obtained based on the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite remote sensing detection. The latitude and longitude ranges of a fire were determined based on the latitude and longitude values of the fire and the FIRMS boundaries.

2.3. Smoke Modeling

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [37] was used to simulate smoke transport and dispersion. HYSPLIT is a complete system for computing simple air parcel trajectories and complex dispersion and deposition. This model uses a hybrid modeling approach of either puffs, particles, or a combination of the two. In the particle model, which was used in this study, a fixed number of initial particles are advected over the model domain by the combined mean and turbulent wind fields. The mean wind fields are the wind field values at the grid points of the input meteorological data. The turbulent wind fields are calculated by HYSPLIT based on the vertical shear of the mean wind fields, atmospheric stability calculated based on temperature, and ground surface roughness which is mainly determined by vegetation type. The plume rise (that is, the height of the smoke plume) is calculated by the model based on the PM_{2.5} emissions and heat release. HYSPLIT uses a simple plume rise algorithm [38] originally developed for power plant stacks. Applications of more complex plume rise algorithms for wildfires [39,40] would possibly improve the smoke transport and the air quality modeling but were not used in this study. The heat release of fire missions was calculated using the scheme described in the Fire Emission Production Simulator (FEPS) [41]. HYSPLIT has been widely used for fire smoke modeling [42–44]. It was used in our recent smoke modeling study of the 2016 Rough Ridge Fire in northern Georgia, USA [45].

The location and size of the simulation domain varied with fire cases. The domain size in the zonal direction (west-east) or the meridional direction (south-north) ranged 10–40 degrees (approximately 1000–4000 km). A resolution of 0.25° (approximately 25 km) and 23 vertical levels (6 in the atmospheric boundary layer up to about 1.5 km above ground level) were used. The option of varied integration time step automatically set each hour by HYSPLIT was selected with the stability ratio of 0.75. The major simulation inputs included fire emissions and meteorology. The fire emissions were obtained from

the gridded Global Fire Emissions Database, version 4 (GFED4) [8], which included small fires [46]. The GFED database was developed based on MODIS products. The resolution was 0.25° (approximately 25 km) with a daily time frequency. There were 32 species and products of fire emissions, including PM_{2.5}, CO₂, CO, NO_x, and SO₂. The simulations included no lateral chemical boundary transport. An evaluation study of burned areas in Daxing'anling showed good agreement in spring but poor in fall between the ground reported and the GFED data [47]. Calculations of fire emissions based on ground reported fire information and measured fuel conditions could improve smoke simulations from fires, especially those occurring in the fall. This approach was not used for this study.

The meteorological variables were from the US National Oceanic and Atmospheric Administration (NOAA) reanalysis with a resolution of 2.5° (approximately 250 km, available until 2007) and the NOAA National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) with a resolution of 1° (approximately 100 km, available from 2005). HYSPLIT includes algorithms to interpolate meteorological fields at modeling grids (including those at lateral boundaries). Meteorological modeling using mesoscale models for the smoke modeling domains would provide high-resolution variables and improve smoke modeling. This approach was not used for this study.

The US Environmental Protection Agency (EPA) Air Quality Index (AQI) color codes [48] were used to assess the human health impacts of smoke. The PM_{2.5} concentration ranges for the codes are as follows. Green (good AQI): $\leq 12 \ \mu g/m^3$; Yellow (moderate): 12.1–35.4 $\ \mu g/m^3$; Orange (unhealthy for sensitive groups): 35.5–55.4 $\ \mu g/m^3$; Red (unhealthy): 55.5–150.4 $\ \mu g/m^3$; Brown (very unhealthy): 150.5–250.4 $\ \mu g/m^3$; Purple (hazardous): $\geq 250.5 \ \mu g/m^3$.

The air quality impacts of smoke were evaluated at local and regional scales based on simulated $PM_{2.5}$ spatial distributions. The size to separate local and regional impacts is indeterminate, but the size of a region usually incorporates one or more cities, and is on the order of 100 to 10,000 km² according to the American Meteorological Society (AMS) [49]. Because fire emissions are an elevated source, which is usually transported much longer in distance than the air pollutants emitted from the surface sources, we used 10,000 km² (100 km in distance or about 4 grid points) to separate local and regional scales. The PM_{2.5} measurements from [50] were used for model evaluation.

3. Results

3.1. Fire Cases in Northeast China

The seven fire cases were classified into three types according to their smoke transport direction and the air quality impacts. (1) Case 1: Smoke was transported from the fire site to densely populated areas in Northeast China with a potentially large human health impact; (2) Case 2: Same as Case 1 except with a potentially small human health impact. (3) Cases 3–7: Smoke was transported to Russia without impacts on densely populated areas in Northeast China.

The Shibazhan fire occurred during 18–27 May 2003 in Daxing'anling near the China-Russia border (Figure 3). Smoke was transported eastward about 500 km into the Russian territory on 23 May (Figure 3a). The $PM_{2.5}$ concentrations were above 250 µg/m³ (hazardous level) in most areas of the smoke plume. Two days later, the direction of smoke transport turned to southeast (Figure 3b). The smoke plume spread over eastern Heilongjiang Province of China. The $PM_{2.5}$ concentrations remained above 250 µg/m³ in the first about 500 km downwind from the fire site with the areas sparsely populated (Figure 2a). The $PM_{2.5}$ concentrations were reduced rapidly thereafter. However, there were still many places with $PM_{2.5}$ concentrations between 35 and 250 µg/m³. The unhealthy conditions due to smoke affected the densely populated areas, including the cities of Mudanjiang and Jiamusi, both with populations of over 2 million. The smoke distributions remained less changed in the next four days (Figure 3c,d) except that the smoke plume spread further southeastward as far as about 2000 km from the fire site.



Figure 3. Simulated smoke plume from the Shibazhan fire. Each square box is a model grid point (approximately 25 km \times 25 km). The names in black are provinces. The green, yellow, orange, red, brown, and purple colors represent good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous air quality levels, respectively. Panels (**a**–**d**) are 18, 21, 24, and 27 May 2003, respectively.

The Wuerqihan fire occurred during 24 May–1 June 2006 in northern Heilongjiang Province, about 500 km southwest of case 1 (Figure 4). Smoke was transported eastward, traveling more than 1000 km into the Russia territory on May 24th (Figure 4a). The $PM_{2.5}$ concentrations reached 55–150 µg/m³ (unhealthy level) in a sparsely populated area a few hundred kilometers from the fire site. Thus, the human health impacts should have been minimal. In addition to eastward direction, the smoke was transported northward. It was also dispersed southward over the entire area of Northeast China during the rest of the fire period (Figure 4b–d). Despite densely populated with many cities, the human

health should have been minimal due to the small $PM_{2.5}$ concentrations of less than 12 μ g/m³ (good air quality level).



Figure 4. Same as Figure 3 except for the Wuerqihan fire. Panels (**a**–**d**) are 26, 28, 31 May and 2 June 2006, respectively.

Two of the five cases are illustrated here for the third type of fires. They were different in fire season and smoke transport direction. The Huzhong fire occurred from 26 June to 3 July 2010, in Daxing'anling (Figure 5). The fire site was located west of the first fire case. Smoke was transported northward across the China-Russia border on 27 June (Figure 5a). The PM_{2.5} concentrations reached 35 μ g/m³ (unhealthy to sensitive groups) locally and in Russia. The smoke was transported continuously northward and northwestward deep into Russia on 29 June (Figure 5b). The PM_{2.5} concentrations increased to more than 250 μ g/m³ (hazardous) inside the border and 55–150 μ g/m³ (unhealthy) outside the border. Smoke transport remained this way until July 3rd (Figure 5c,d) inside the border with very high PM_{2.5} concentrations. In addition, there was smoke plume development toward south on 3 July. The human health impacts should have been minimal in these sparsely populated areas on 3 July when the unhealthy portion of smoke did not go south enough to reach the moderately and densely populated areas.



Figure 5. Same as Figure 3 except for the Huzhong fire. Panels (**a**–**d**) are 27 and 29 June and 1 and 3 July 2010, respectively.

The Yichun fire occurred during a fall period of 3–7 October 2007 in Heilongjiang Province by the China-Russia border (Figure 6). Smoke was transported eastward and northeastward into Russia with small PM_{2.5} concentrations (good air quality) on 4 October (Figure 6a). It appeared that the fire intensified and spread toward the south on the next day leading to a line of dense smoke longer than 500 km (Figure 6b) with sparsely and moderately populated areas. The PM_{2.5} concentrations were over 250 μ g/m³ (hazardous). The smoke was transported further south into Russia where the PM_{2.5} concentrations were 55–150 μ g/m³ in the following two days (Figure 6c,d). Thus, the high PM_{2.5} concentrations should have had a moderate impact on human health in some areas.

For three other fires of the third type (illustrated in Appendix A), the Huma fire occurred near the Yichun fire site also during the fall (24–31 October 2005) (Figure A1). The smoke was transported to east and southeast. The PM_{2.5} concentrations of more than 250 μ g/m³ affected some moderately populated areas. The Songling fire occurred in Daxing'anling, northwest of the Yichun fire site, during 22 May to 2 June 2006 (Figure A2). The smoke was transported to east, northeast, and north. The PM_{2.5} concentrations of more than 250 μ g/m³ affected sparsely populated areas. The Yimuhe fire occurred further west during 1–4 June 2006 (Figure A3). The smoke was transported north with minimal health impacts.



Figure 6. Same as Figure 3 except for the Yichun fire. Panels (a-d) are 4, 5, 6, and 7 October 2007, respectively.

3.2. Fire Cases in North China

The fires and smoke transport were classified into two types. (1) Cases 8–10: Fires with smoke transported mainly in one direction; (2) Cases 11–13: Fires with smoke transported in two or more directions.

The Baoding fire occurred during 6–8 April 2014 in Hebei Province, about 500 km southwest of Beijing, the nation's capital (Figure 7). Smoke was transported eastward on 7 April reaching south of Beijing (Figure 7a). The PM_{2.5} concentrations were small, about 12 μ g/m³ at the fire site and another spot about 100 km away in the northeast. Smoke continued to move east the next day with PM_{2.5} concentrations increased to 55–150 μ g/m³ (Figure 7b) in a local area of densely populated (Figure 7b). Thus, the smoke led to unhealthy air quality mainly near the fire site, which should have affected human health. The measurements of PM_{2.5} were available for this fire case (Figure 8). The measured values were stable at about 40 μ g/m³ on the three days prior to the Baoding fire. The values increased to about 65, 93, and 151 μ g/m³ on the three days of the fire period. The contributions from the fire (excluding the background concentrations) were about 50 μ g/m³ on 7 April and 110 μ g/m³ on 8 April. Thus, the simulated PM_{2.5} concentrations were comparable to the measured magnitude on 8 April but slightly underestimated on 7 April.



Figure 7. Same as Figure 3 except for the Baoding fire. Panels (a-b) are 7 and 8 April 2014, respectively.



Figure 8. Measured $PM_{2.5}$ concentrations ($\mu g/m^3$) in Baoding.

The Yangquan fire occurred during 29 April–1 May 2011, in Shanxi Province (Figure A4). Smoke was transported mainly southeastward, reaching the southeastern coast about 1500 km away. The Weihai fire occurred during 30–31 May 2014, in the coastal area of Shandong Province (Figure A5). Smoke was transported northeastward. The PM_{2.5} concentrations from either fire were smaller than $35 \ \mu g/m^3$.

The Funing fire occurred from 12 to 18 April 2011 in Hebei Province, less than 500 km east of Beijing (Figure 9). On 14 and 15 April, smoke was transported northeastward to Northeast China and eastward to the sea area (Figure 9a,b). The smoke continued to move this way the following two days, but in the meantime, smoke was also transported southward to South China (Figure 9c,d). The PM_{2.5} concentrations were smaller than 12 μ g/m³ during the entire fire period. Thus, smoke from this fire spread over densely populated areas but should not have had much impact on human health. The smoke from either the Laiwu fire occurring during 17–19 April 2011 (Figure A6) or the Jinan fire occurring during 18–20 April 2011 (Figure A7) in Shandong Province was similar to that from the Funing fire, but spread in two directions of northeast and south only over the land areas.





Figure 9. Same as Figure 3 except for the Funing fire. Panels (a-d) are 14, 15, 16, and 17 April 2011, respectively.

3.3. Fire Cases in Southwest China

The Chuxiong fire (case 14) occurred during 23–28 April 2013 in Yunnan Province (Figure 10). Smoke was transported eastward to form a smoke line of over 1000 km long from central Yunnan Province to eastern Guizhou Province on 24 April (Figure 10a). The PM_{2.5} concentration was 35–55 μ g/m³ near the fire site. It affected Kunming, the province capital with a population of 6 million people. The concentrations were very small in other areas. The smoke started to disperse southward on 26 April reaching the coastal area of Guangxi (Figure 10b). In the following days, the smoke further spread toward the east and north. The PM_{2.5} concentrations remained small (Figure 10c,d). The transport of smoke from two other fires (cases 15–16) in Southwest China was similar to that of the Chuxioang fire except that the PM_{2.5} concentrations from the Dali fire were smaller than 12 µg/m³ (Figures A8 and A9).

3.4. Discussion

The simulation results of the16 fire cases summarized in Table 2 indicate that the investigated fires in the Northeast region occurred in the remote mountains north of the densely populated areas. The PM_{2.5} concentrations reached the hazardous level for most cases. However, smoke was transported to the sparsely populated areas for a majority of fire cases. Smoke affected densely populated areas only for one fire case and moderately populated areas for two fire cases. The locations and impacts of the fires in this region were similar to those in the Rocky Mountains of the United States.



Figure 10. Same as Figure 3 except for the Chuxiong fire. Panels (a-d) are 26-29 April 2013, respectively.

Table 2. Smoke transport and air quality impacts. S and Rus in parenthesis represent sensitive groups and Russia, respectively. The population density is the population density classification of the areas in China where smoke PM_{2.5} concentrations reached the level of unhealthy to sensitive groups or worse.

Reg	No.	Name	Site Relative to Cities	Transport Direction	Air Quality Impact		Population Donsity
				Transport Direction	Local	Regional	i opulation Density
- Northeast - -	1	Shibazhan	north	southeast	hazardous	hazardous	dense
	2	Wuerqihan	north	East, north	unhealthy	good	sparse
	3	Huzhong	north	mainly north	hazardous	unhealthy (Rus)	sparse
	4	Yichun	north	east, south	hazardous	unhealthy (Rus)	moderate
	5	Huma	north	east, southeast	hazardous	hazardous (Rus)	moderate
	6	Songling	north	north, northeast	hazardous	hazardous (Rus)	sparse
	7	Yimuhe	north	north	very unhealthy	very unhealthy (Rus)	sparse
- North - -	8	Baoding	west	east	unhealthy	moderate	dense
	9	Yangquan	west	southeast	good	good	dense *
	10	Weihai	east	northeast	moderate	moderate	dense *
	11	Funing	surrounding	east, south	good	good	dense *
	12	Laiwu	surrounding	northeast, south	good	good	dense *
	13	Jinan	surrounding	northeast, south	good	good	dense *
Southwest -	14	Chuxiong	west	east	unhealthy (S)	good	dense
	15	Anning	west	northeast	unhealthy (S)	good	dense
	16	Dali	west	northeast	good	good	dense *

* The area where smoke PM_{2.5} concentrations were at either good or moderate level.

In contrast, smoke from all nine fires in North and Southwest China was transported to densely populated areas. However, the $PM_{2.5}$ concentrations reached the level of unhealthy to sensitive groups

only in local areas for three fire cases. Thus, the regional air quality and human health impacts of these fires were minimal. One reason for the minimal regional impacts was that the Chinese government had implemented a strict forest fire suppression policy since the catastrophic 1987 Black Dragon fires in Daxing'anling [51]. A fire would be suppressed as soon as possible. Once a fire was observed, the local government was notified immediately, and it determined the amount of human resources to deploy to fight the fire [52]. As a result, most fires would grow slowly and diminish in a period of a few days. Thus, burned areas and emissions of these fires were mostly small with only minimal impacts on air quality downwind.

The evaluation of the modeling results suggested a difference in the contributions of fire smoke to regional air quality and human health between the China regions and some other fire regions in the world such as the United States. The $PM_{2.5}$ concentrations from non-fire sources in Figure 8 was about 40 µg/m³. This value was comparable to the average values for the eastern China from a global analysis [19]. The concentrations in the continental US from the analysis were less than half of the values in China. The $PM_{2.5}$ concentrations on 8 April 2014 from the Baoding fire were at the unhealthy level. With the background value, however, the total $PM_{2.5}$ (measured) reached the very unhealthy level. Thus, although the $PM_{2.5}$ concentrations from fires in the North or Southwest region of China usually were small, air pollutions could be still heavy during a smoke period because of the large background $PM_{2.5}$ level.

The impact of smoke from fires in Northeast China on air quality in Russia is a concern for the fire and air quality management in both China and Russia. A related issue is smoke transport into China from fires in Russia. The Euro-Asia boreal, mainly in Siberia, is one of the major wildfire regions in the world. The fire number, size, intensity, and duration in this region usually are much more than those in Northeast China. Smoke from the fires in Siberia can be transported a long distance to affect air quality in eastern Asia including China. For example, the smoke from the 2003 spring Siberia fires was transported to Northeast and North China with $PM_{2.5}$ concentrations exceeding 55 µg/m³ (unhealthy) [53]. Further research is needed to simulate the across-boundary smoke transport to improve the assessment of the contributions of wildfires to the air pollutions in China.

One of the limitations with this study is that only a limited number of fire cases were simulated. Because the spatial extend and magnitude of exposures and resultant health outcomes depend on the location, timing and duration of wildfires as well the prevailing meteorological conditions, the results from this study only included certain spatial patterns and magnitude of smoke transport and impacts. The fire cases in the Northeast region simulated in this study included major largest fires in this region during recent two decades, including the fires during 2003 and 2006 when nearly 9000 km² and 4700 km² were burned, respectively, much more than other years during the two-decade period (Figure A10). Fires in the North and Southwest regions were usually much smaller than these in the Northeast region because of the moister conditions (especially in the Southwest region) and better accessibility for fire suppression due to closer fire sites to densely populated areas (especially in the North region). Also, fires usually occurred either in the mountains west of the downwind densely populated areas or within densely populated areas. Thus, it is expected that the simulation results of the fire cases investigated in this study, despite a small number, reflected some general spatial patterns and magnitude of smoke transport and impacts in the two regions.

4. Conclusions

Smoke has been simulated for more than a dozen wildfires in the Northeast, North, and Southwest China. The regional differences in smoke transport and the air quality and human health impacts obtained from the modeling results provided evidence for the hypothesis for this study, that is, individual fires with very large sizes in Northeast China had a large amount of emissions but a small chance to affect air quality in densely populated areas, while fires in North and Southwest China usually had small emissions with large local impacts in some cases. This finding suggests that the fire

and air quality management should focus on fires with very large sizes under wind directions toward the south in Northeast China and local air pollutions from fires in the North and Southwest China.

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Appendix A



Figure A1. Simulated smoke plume from the Huma fire. Each square box is a model grid point (approximately 25 km \times 25 km). The names in black are provinces. The green, yellow, orange, red, brown, and purple colors represent good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous air quality levels, respectively. Panels (**a**–**d**) are 25, 27, 29, and 31 October 2005, respectively.



Figure A2. Same as Figure A1 except for the Songling fire. Panels (**a**–**d**) are 25, 28, and 31 May and 3 June 2006, respectively.



Figure A3. Same as Figure A1 except for the Yimuhe fire. Panels (a-d) are 1, 2, 3, and 4 June 2006, respectively.



Figure A4. Same as Figure A1 except for the Yangquan fire. Panels (**a**–**c**) are 30 April and 1 and 2 May 2011, respectively.



Figure A5. Same as Figure A1 except for the Weihai fire. Panels (a,b) are 30 and 31 May 2014, respectively.



Figure A6. Same as Figure A1 except for the Laiwu fire. Panels (a-c) are 17, 18, and 19 April 2011, respectively.





Figure A7. Same as Figure A1 except for the Jinan fire. Panels (a-c) are 19, 20, and 21 April 2011, respectively.



Figure A8. Same as Figure A1 except for the Anning fire. Panels (**a**–**d**) are 30 March and 2, 5, and 8 April 2006, respectively.



Figure A9. Same as Figure A1 except for the Dali fire on 8 March 2007.



Figure A10. Annual burned areas in the Northeast China region.

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