Canadian Wildland Fire & Smoke Newsletter

Fall 2016

"Connecting diverse wildland fire, emissions, air quality and modelling communities."

Wildfire rips through the forest south of Fort McMurray, Alberta. on Highway 63 May 7, 2016. (Photo: Jonathan Hayward/Canadian Press)

The Fort McMurray Wildfire: By the Numbers

by Mike Flannigan[1] and Cordy Tymstra[2]

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A brief look back: The Fort McMurray wildfire, officially called the Horse River Wildfire (MWF-009), started on Sunday May 1, 2016. This human-caused wilfire was discovered at 16:03 MDT by a helitack crew flying nearby, patrolling the area for wildfires. The investigation is ongoing to determine the exact cause of the wildfire.

The wildfire was declared under control July 4, 2016, with a size just less than 590,000 hectares, which is approximately the size of Prince Edward Island. The wildfire reached Fort McMurray on May 3rd, and resulted the evacuation of nearly 90,000 people from the Regional Municipality of Wood Buffalo. Almost twenty –six hundred structures were lost due to the wildfire; the insurable losses are estimated at $3.77 billion making it the costliest insured claims disaster in Canadian history and the second most costly wildfire globally. The drop in Canadian Gross Domestic Product this summer was in large part directly due to shutdowns of oilsands production caused by the wildfire. Alberta Agriculture and Forestry reached daily maximums of various firefighting resources in May and June: 1,590 wildland firefighting personnel from Alberta, across Canada and other jurisdictions on June 6, 64 bull-dozers on May 16, and 79 helicopters (not including heavy classed helicopters) on June 7.

In this Issue:

The start of the wildfire coincided with a record breaking heatwave (Table 1) that was preceded by a mild dry winter and spring due to a very strong El Nino. At the Fort McMurray International Airport, the winter temperatures were about 4° C warmer than normal, while precipitation was around half of normal. Additionally, extremely dry fuels combined with shifting and gusty winds at the beginning of May made wildfire suppression very challenging.

What the numbers do not convey is the impact on people affected by the wildfire. Residents of Fort McMurray and surrounding area were displaced for many months; some are still waiting for their homes to be rebuilt. Firefighters (both wildland and community - structural) and other first responders such as police and emergency management personnel worked tirelessly to protect the people and the community. The memory of this wildfire will last a lifetime. One of the silver linings on this event is the way the community, the province and the country pulled together to help those in need.

Figure 1. Photo taken in early May shortly after the fire near Fort McMurray Airport

Figure 2. Aspen regrowth in burned stand near Fort McMurray Airport. (Photo: Xinli Cai)

Wright Award

For excellence in wildland fire research and significant contributions to the advancement of wildfire management in Canada, Brian Stocks received the Wright Award at the 2014 Wildland Fire Canada conference in Halifax. Brian has had difficulty coming to terms with retirement, as he continues to work on a number of wildland fire projects.

Day	Max. Temp	Min RH	Max RH	Prec	Max. Wind &Gust
	°C	%	%	mm	Km/h
1-May	25	15	64	0	22 G33
2-May	27.4	22	77	0	17 G31
3-May	32.8	13	58	0	24 G72
4-May	31.9	14	58	0	50 G69
5-May	18.8	17	40	0	30 G48
6-May	19.2	15	60	0	22 G41

Table 1. Fort McMurray weather conditions during the first 6 days of May 2016.

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Departed Fire Regime Conditions from Historical References are Raising Concerns in Southern Alberta

by Marie-Pierre Rogeau

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This article is a summary of the doctoral thesis [Rogeau 2016] I recently completed at the University of Alberta under Dr. Mike Flannigan. My research documented the fire history and fire regime of a large landscape in southern Alberta, which straddles three natural subregions: Montane, Subalpine and Upper Foothills (Figure 1). The 6677 km^2 study area lies west of Calgary and is bound by the Little Red Deer and Sheep Rivers. It comprises the forested portion of watersheds forming the headwaters of many tributaries that eventually flow into the Bow River. The entire area is valued on many fronts. The vast forest cover protects the waters' pristine conditions, which are the potable water source for the regional population of Calgary. The region receives varying degrees of forest harvesting protection, but a large portion of the forest is part of an important timber pool managed under a Forest Management Agreement. The entire region is also a mecca for various recreational activities such as hiking, ATV use, camping, hunting, fishing, skiing and snowshoeing.

The forested hills and mountains are easily accessible and enjoyed by many, including those who wish to live in these ecosystems. One downside is the proximity of communities to dense forested areas, which increases their risk of fire losses. In recent years the Friends of Kananaskis Country (a group aiming at protecting the forest from logging and broad-scale prescribed burning) challenged the Government of Alberta's attempt to reduce fire risk at the Wildland Urban Interface (WUI). The romanticized view of some vocal residents regarding the beauty of a green forested landscape, contrasted with the need to let nature takes its course in terms of wildfire occurrence, has made fuels management challenging to say the least. Non-action could have devastating effects not only on the Bragg Creek community itself (as an example), but could also have severe repercussions for the overall protection of headwaters. There is a critical need for public education to help people understand about past fire frequencies and their probabilities, and how continued fire suppression over several decades is affecting fuel condition

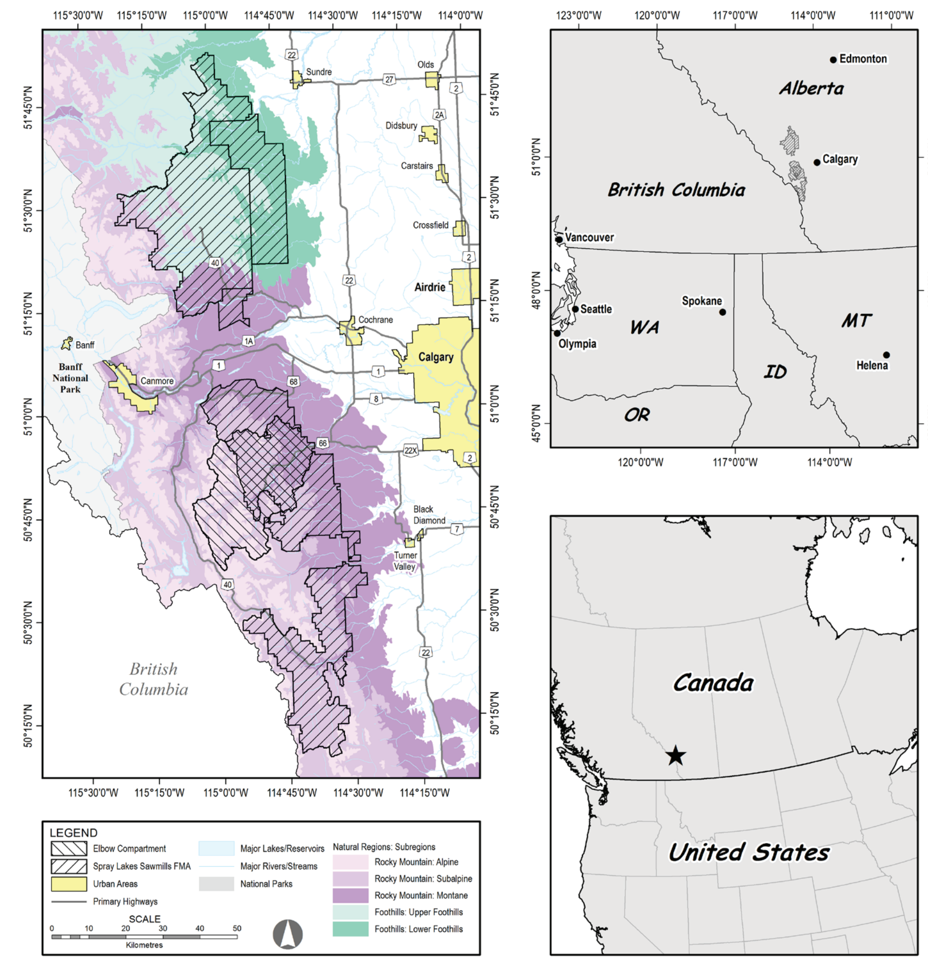

Figure 1. Study Area

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and future ability to fight and control fires. Adding to the existing fire risk at the WUI, conditions of higher fire intensities and resulting fire severities are amplified by a warming climate and an extended fire season as per recent conflagrations in Fort McMurray (2016) and Slave Lake (2011).

In southern Alberta – and for most of Alberta, fire used to be an integral part of the landscape. The following section highlights my research results. I conclude with a discussion of potential consequences of a departed fire regime towards long fire intervals and the implications for fuels management.

Research Summary

I used tree-ring data from 3123 cross-sections collected at 814 sampling sites to document fire return intervals (FRI) within six sampling units ranging in size from 7158 to 43,848 ha [Rogeau, et. al. 2016]. A FRI is defined as the number of years between two fire events at the sampling site. The research questions were the following:

1. Historically, was the fire regime homogeneous across the entire landscape?
2. Did the historical fire regime vary spatially by natural subregion?
3. Can we expect the fire regime to be homogeneous within a natural subregion?
4. In this mountainous landscape, are there spatial variations in the FRI correlated to topographic variables such as elevation and aspect?
5. Has the FRI significantly changed since effective fire suppression (post-1948)?

The period of most effective fire suppression started in 1948 and corresponds to the establishment of the Eastern Rockies Forest Conservation Board [Murphy 1985]. The mandate of the Board was to protect the forest cover of the East Slopes headwaters from fire by injecting a large amount of money for capital expenditures such as building roads, trails, fire lookouts and communication towers, and hiring extra personnel. Since 1948, only a handful of fires became Class E fires (>200 ha) and the total area burned within the study area has been less than 20 000 ha over a period of 68 years. On average, this amounts to 300 ha of forest burned per year, or 0.04% of the landscape, and it corresponds to a fire cycle of approximately 625 years in the Subalpine and of over 5000 years in both the Montane and Upper Foothills natural subregions. The fire cycle is the time required to burn an area equivalent to the size of the area of interest. Fire cycle and FRI values are not directly interchangeable, but both

Region	Pre-1948	Post-1948	% dep.
MG[1]	32	95	197
MH[1]	26	84	223
ME[1]	35	104	197
UF[2]	39	104	167
SH[3]	65	148.5	129
SE[3]	85	121	42

[1] Montane, [2] Upper Foothills, [3] Subalpine

Table 1 Kaplan-Meier probability median FRI pre- and post-1948 and percentage of departure by sampling unit. ME: Montane-East, MG: Montane-Ghost, MH: Montane-Highwood, SE: Subalpine-Elbow, SH: Subalpine-Highwood, UF: Upper Foothills.

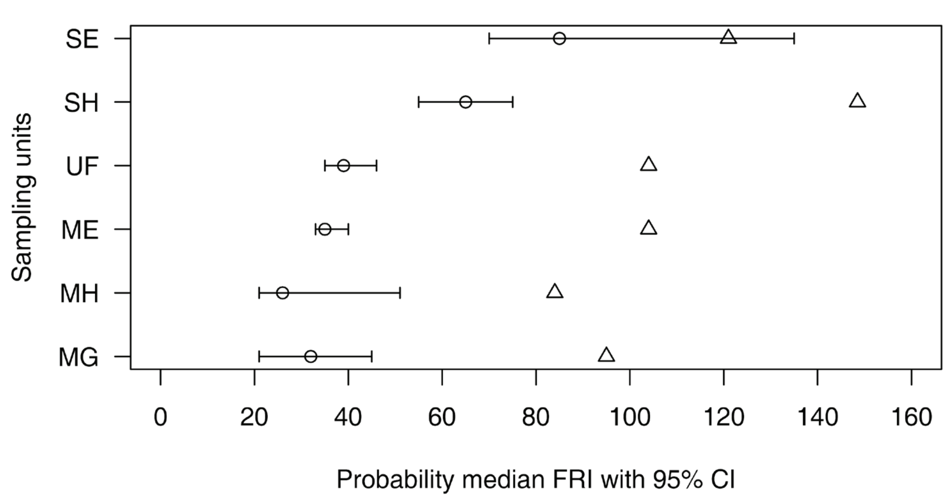

Figure 2 Median FRI since the onset of effective fire suppression (triangle) in comparison to the natural range of variation depicted by the 95% lower and upper confidence intervals of the Kaplan-Meier probability median fire interval. ME: Montane-East, MG: Montane-Ghost, MH: Montane-Highwood, SE: Subalpine-Elbow, SH: Subalpine-Highwood, UF: Upper Foothills.

can point to a changing fire regime.

FRI analyses (Table 1 and Figure 2) showed contemporary fire interval values for the Montane and Upper Foothills to be significantly different than historical conditions. In contrast, the most rugged portions of the Subalpine were found to still be within their natural range of variation.

As portrayed in Table 1 and Figure 2, FRI were not historically homogenous across the entire landscape and statistical testing revealed significant differences between natural subregions. Natural subregions are defined by their topographic terrain, elevation, vegetation, and climate among other things. These features are closely related to the fire environment and as such, natural subregions appear to be logical partitions for fire management when dealing with large landscapes. However, spatial variability in FRI was also observed within natural subregions especially for the Subalpine. The level of forest dissection by rocky ridges and the extent of fuel continuity greatly influence the length of FRI. Headwaters and small, narrow valleys from rugged landscapes showed to have much longer FRI than main valleys, which tend to have shorter FRIs due to a combination of extensive forest cover leading to larger size fires and greater fire occurrences from a history of higher human land use.

In mountainous landscapes, elevation and aspect are significant variables affecting FRI. Elevation is pertinent for all natural subregions, whereas aspect is only relevant in the Subalpine where high mountains cast long shadows and have a notable effect on fuel moisture. For every 100m of elevation gain, the probability of fire decreases by 10, 20 and 30% for the Montane, Upper Foothills and Subalpine, respectively. For aspect, a south facing slope is nearly twice as likely to burn (i.e. 95% higher probability) than a cool aspect.

In terms of documenting other aspects of the historical fire regime, the highlights of this research were the converging lines of evidence towards a fire regime dominantly shaped by human-caused fires. The Canadian Rocky Mountains, east of the Continental Divide, are in a lightning strike shadow where few lightning strikes occur. The number of strikes increases in the Upper Foothills where 58% of fires have been caused by lightning in the contemporary era. Only 25% of fires are caused by lightning in the Subalpine and they tend to occur in July and August. In the Montane, contemporary data indicate a low 10% of fires are caused by lightning and there is strong evidence such low proportions were maintained historically. The intra-ring positions from a large number of fire scars point to a prevalence of spring and fall fires during which time the grass is cured, yet the probability of lightning strikes is low.

A number of factors pointed to a historical fire regime of mixed severity (less than 75% tree mortality) for the Montane and Upper Foothills, while high severity fires prevailed in the Subalpine. Many stands in the Montane and Upper Foothills had evidence of more than three fires. Of great surprise, a considerable number of felled lodgepole pine trees during the study revealed healed over fire scars when trees were at the sapling stage. An indication that fire intensity had to be low for these trees to survive. The assumption of low fire intensity and low fire severity is corroborated with the short fire intervals of 26 to 35 years documented in the Montane, where the accumulation of dead woody debris and large diameter fuels would have been unlikely. Mountain Legacy Photography (http://mountainlegacy.ca/) taken during irrigation and topographic surveys of the Canadian Rockies at the turn of the 19th century show a landscape frequently burned (Fig. 3). From a fire ecology perspective, lodgepole pine (Pinus contorta subsp. latifolia Loudon) starts producing both serotinous and open cones as early as 7 years (pers. obs.) as a means to survive fire and ensure seed availability under such short fire intervals. It is important to understand that while the fire regime may be characterized as mixed-severity, lodgepole pine forests do not survive fire well and often result in significant tree mortality. Such fires can be characterized as a stand replacing fires.

Implications of a changing fire regime

The study results showed that prior to the onset of effective fire suppression, the Montane and Foothills of the Canadian Rockies of southern Alberta had some of the shortest fire return intervals documented in Canada for a stand replacing fire regime. The lengthening of fire intervals, and the overall fire cycle, since the early 1950s is transforming forests into homogenous mature stands displaying characteristics normally associated with forests regulated by an infrequent stand replacing fire regime and typical to those documented in the subalpine

Elbow watershed. Photo taken by A. Wheeler, 1897, South Quirk photo station (Source: Mountain Legacy Project)

Repeat photography taken in 2014 by the Mountain Legacy Project team.

Figure 3 Example of a Montane landscape showing turn of the 19th century forest mosaic of small diameter trees as a result of short interval burning (top), compared to homogeneous pine forest conditions (2014) (bottom).

natural subregion of the main ranges of the Canadian Rockies.

When compared to historical photographs from the early 1900s (http://mountainlegacy.ca/), the maturing forests are denser, contain larger diameter trees, and are developing a complex vertical fuel structure resulting not only from trees dying off and falling, but also from an important sub-canopy spruce layer infiltrating mature pine stands. Such fuel complexity and structure enhance the probability of low intensity fires quickly morphing into intense canopy fires. Under the combined pressure of a warming climate and sustained drought conditions, we have observed high-severity post fire effects in recent years, where mineral soil is extensively exposed and where fewer green islands remain within the fire perimeter (2001 Dog Rib fire west of Sundre, 2014 Spreading Creek fire in Banff National Park, and recent fires in Willmore Wilderness Park).

High severity fires are concerning for a number of reasons. The extensive area of ground fuels (i.e. duff) stripped away can lead to intense erosion after rain events and spring snow melt, which in turn increase the turbidity in streams. For several years following the 2003 Lost Creek fire (Crowsnest region of southern Alberta), researchers documented significant levels of contaminants in streams including heavy metals that had been released from the burnt duff [Bladon, et. al. 2008; Silins, et. al. 2009]. High severity fires also result in a delayed recruitment of vegetation and seedlings, which adds to the compounding effect of soil instability, and which is further exacerbated in a mountain setting of moderately steep angled slopes. These negative effects are particularly concerning for the region of Calgary and surrounding municipalities that draw their water supply from forested upslope mountain streams.

Of additional consideration under a warming climate is the important release of CO^{2} in the atmosphere all at once during large conflagrations, rather than a controlled release of smaller amounts through the use of prescribed burns [Carey, et. al. 2001; Mitchell, et. al. 2009]. The delayed post-fire regeneration resulting from high severity fires also means an extended time period for the carbon sink to re-establish itself to levels similar to the pre-fire period.

From an ecological perspective, highly valued biological entities such as old-growth forests and fire refugia (areas that can repeatedly escape burning due to their topographic location) are also now at greater risk of burning under a stand replacing fire regime of increased fire intensity. Historically, the short fire intervals kept the fuel load in check and fire intensity was usually too low for a fire in a young pine stand to move into an old stand with higher moisture conditions as a result of a thicker duff layer, larger diameter trees and a denser canopy layer. The repeat burning that historically took place in pine stands created a marked difference in canopy height between a young pine stand versus an old spruce-fir one. The fuel structure difference between the two seral stage types was often enough to mitigate important burn encroachment from young pine stands burning into old forests. Today, the homogenizing of forest stands and canopy height offer little barrier to protect old-growth and fire refugia from burning. The first few kilometres from headwaters, and high elevation north facing slopes, are prime locations of fire refugia in the mountains [Camp, et. al. 1997; Rogeau, et. al. 2004]. The risk of losing fire refugia to large, high severity fires would have devastating consequences for the integrity of streams as well as for the important ecological functions that old-growth forests fulfill in an ecosystem. The older the forest is at time of burning, the more time it has had to capture atmospheric contaminants, and the greater the amount of such contaminants will be released into water streams. Old-growth forests are also important carbon pools [Paw, et. al. 2004].

Conclusions

It is imperative for forest and fire managers to mitigate the size and severity of future wildland fires. Criteria to manage fuels need to be established to meet various objectives across different spatial scales. At the WUI, this is a necessary practice not only adjacent to structural buildings and along the immediate interface, but also away from the interface in a landscape context to create a wide defensible zone. Landscape level fuels management involves large mechanical disturbances and prescribed burns that can be done in a way that emulates past disturbances (in terms of patch retention and intervals between treatments).

However, given the unpopularity of broad scale fuels management that involves clearcutting or burning due to the perceived unappealing changes to the viewscape, as well as concerns for wildlife and stream bank erosion, education of and communication with the public are pre-requisites for successful implementation and management of fires in Alberta [McFarlane, et. al. 2011]. Strong evidence of an anthropogenic fire regime in southern Alberta, which historically shaped these fire adapted ecosystems, suggests that it is possible for mankind to continue to manipulate the fire regime in ways that will achieve our needs and goals in the future.

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Impact of the 2010 Russian Wildfires on Moscow's Air Quality

by David Lavoué[1] and Aika Davis [2]

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In the summer of 2010, the densely populated region of Moscow (17 million inhabitants within its urban area) was dramatically affected by heavy smoke emitted by several hundred wildland fires burning in the forest and peatland of western Russia (Figure 1). The vast majority of the fires were most likely of human origin including negligent use of agricultural fires, accidental fires during forestry operations, and leisure fires such as barbecue fires and fireworks [Goldammer, 2010].

Western Russian fires were in fact relatively small compared to other fires burning east of the Ural Mountains. By mid-August, Western Russian fires had affected 300,000 to 400,000 hectares of forest and peatland, whereas the area burned in central and eastern Russia had reached millions of ha according to satellite-derived data. The Global Fire Monitoring Center in Freiburg, Germany states that the total area burned in the Russian Federation by 18 August 2010 was close to 6 million ha (http://www.fire.uni-freiburg.de/, accessed 14 September 2016).

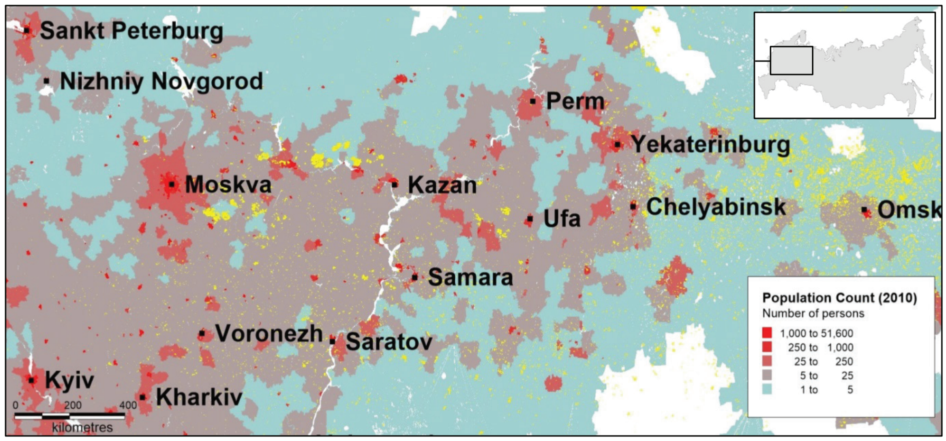

Figure 1. Area burned (in yellow) by forest and peat fires in western Russia in 2010. Population count is given as the number of persons/grid cell (30 arc second ~1km) [*Center for International Earth Science Information Network - CIESIN - Columbia University, 2016*]. Moscow is the most populous city of the Russian Federation with nearly 17 million residents within its urban area.

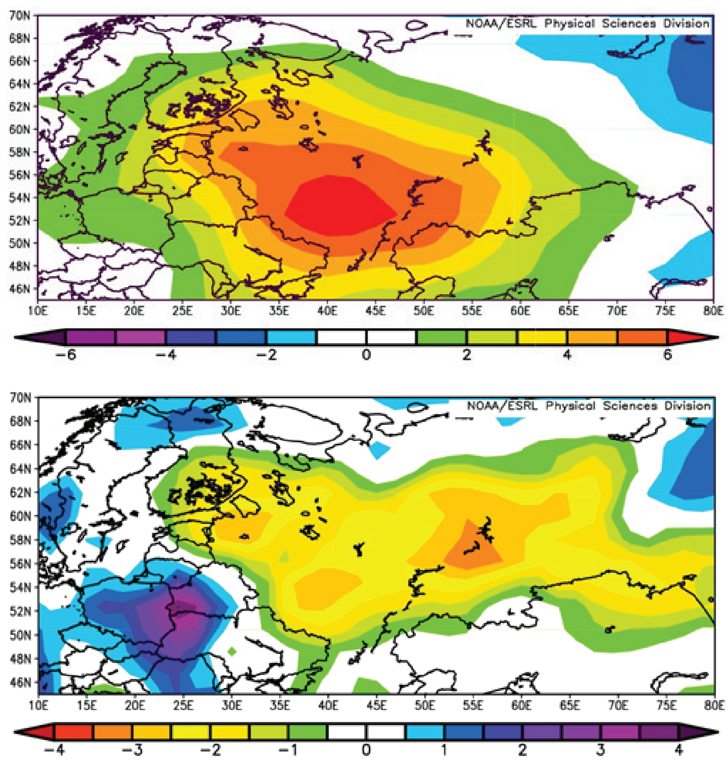

Figure 2: Composite anomaly for surface air temperature in °C (a) and precipitation rate in mm/day (b), during the period of July 1-August 31 2010. Calculation is based on 30 years of climatology (1981-2010) from NCEP/NCAR reanalysis.

Weather Conditions in Russia in the Summer of 2010

Western Russian fires' rapid growth was fueled by record-high temperatures and severe drought conditions. Daily composites of anomalies (i.e., mean minus total mean) of air temperature and precipitation rate calculated on NOAA's Earth System Research Laboratory website (http://www.esrl.noaa.gov/psd/data/composites/day/, accessed 19 September 2016), point out a positive anomaly for temperatures in July and August at a continental scale (Figure 2a); a large portion of European Russia was more than 5 °C warmer than usual. Figure 2b shows a negative precipitation anomaly spanning much of Russia.

The summer of 2010 was the hottest since weather observations started in the Russian capital 130 years ago. Record high temperatures were observed in Moscow from the end of June until the beginning of August (http://rp5.ru/archive.php?wmo_id=27612&lang=en). For three months, average high, daily mean and average low temperatures were systematically over the averaged values for 1961-1990, corresponding to an official 30-year normal period defined by the World Meteorological Organization (WMO) (Table 1). On July 29th, the city was scorched by 38 °C heat whereas average summer temperature is around 23 °C . The July average high was 8 °C above the 1961-1990 normal. Nights were also much warmer than usual.

Month	June	July	August
Record high	33.4 (26 Jun)	37.8 (29 Jul)	36.6 (4 Aug)
Average high	26.7 *21.7*	31.4 *23.1*	23.4 *21.5*
Daily mean	18.8 *16.6*	21.1 *18.2*	21.8 *16.4*
Average low	13.8 *11.5*	20 *13.5*	16.7 *12*

Table 1: Temperature records (°C) at the VVC weather station in Moscow (WMO #27612) in 2010. The 1961-1990 normals are indicated in italic (https://en.wikipedia.org/wiki/Moscow#Climate, accessed 16 September 2016).

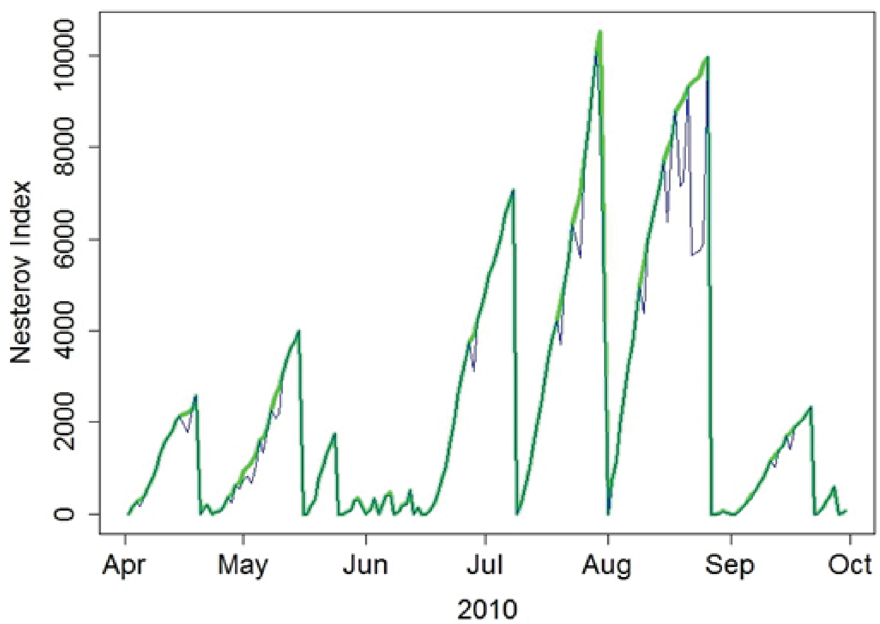

Figure 3: Nesterov Index (in green) and Modified Nesterov Index (in blue) from April through September 2010 in the region of Moscow (55°45′N, 37°37′E). Four fire danger classes are usually considered based on NI or MNI values: minimal (0-300), moderate (301-1000), high (1001-4000) and extreme (4001+).

Fire Danger

The daily variation of fire danger during the snow-free months of 2010 was determined with the Nesterov Index (NI). NI is a fire-danger rating system that was developed by Nesterov [1949] just after the Second World War. Its calculation integrates the number of days since the last rainfall exceeding 3 mm/day, and the air temperature and dew point temperature on a given day. The index establishes several discrete fire-risk levels: minimal, moderate, high and extreme. Since NI was found to be unstable in certain weather conditions, Groisman et al. [2005] developed the Modified Nesterov Index (MNI) to account for different classes of daily rainfall. Figure 3 exhibits daily variation of both NI and MNI from April through September from weather observations in the Russian capital. It clearly shows that fire danger in the Moscow region was high to extreme from mid-June through the third week of August.

Air Quality Impact

Beginning in August, hundreds of forest and peat fires generated notably large smoke plumes covering

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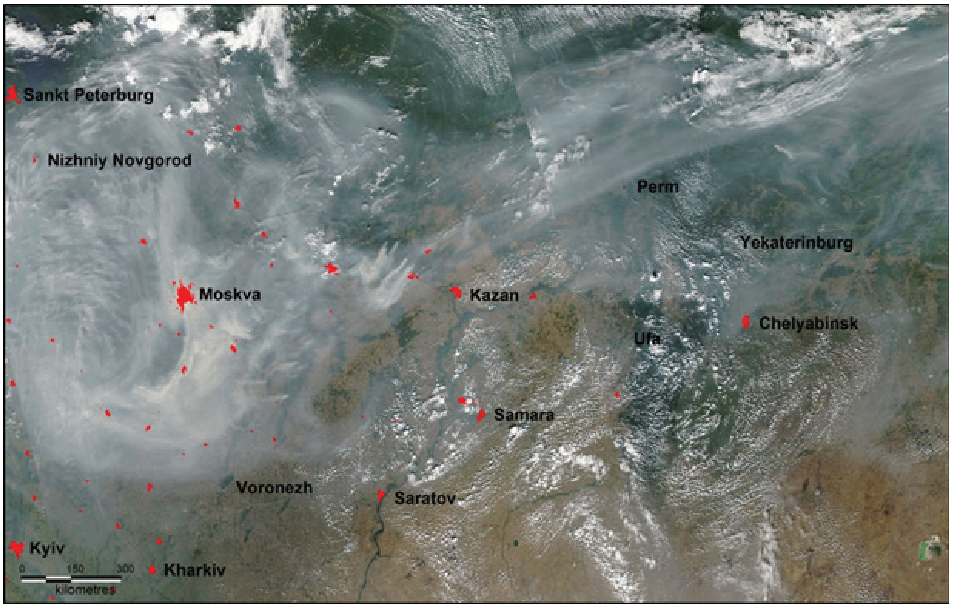


Figure 4: MODIS image of smoke plumes over Western Russia, 7 August, 2010 (image courtesy of NOAA/NASA). Red polygons correspond to areas with population count of 1000+/km^2 [Center for International Earth Science Information Network - CIESIN - Columbia University, 2016].

Western Russia (Figure 4) for many consecutive days as shown by MODIS imagery. Remote sensing also revealed that smoke was drifting towards neighboring countries as far north as Finland [Mielonen et al., 2013].

During the first week of August, an anticyclone with dry air hovered over Moscow [Sofiev et al., 2011]. The temperature inversion inhibited free convection and thick smoke blanketed the city causing significant visibility reduction. From 9 p.m. on August 6th to 12 p.m. on August 8th, visibility was consistently below 1 km. At 3 p.m. on August 7th, visibility dropped to 50 m. Furthermore, the AERONET site located at Moscow State University (http://aeronet.gsfc.nasa.gov/, accessed 14 September 2016) measured aerosol optical depth (AOD) values up to 4 and 5 on August 7th and 8th, respectively. AOD is a measure of the extinction of the solar beam by suspended particulate matter in the atmosphere and a value of 0.4 usually corresponds to very hazy conditions.

Ambient air quality monitoring stations across the Moscow region recorded hazardous levels of many air pollutants, including ozone (O_3), carbon monoxide (CO) and Particulate Matter (PM), affected millions of people. At one station, eight-hour averaged O_3 concentrations exceeded 120 μg/m^3 for 30 days beginning July 19th, with a peak at 344 μg/m^3 on August 6th. In the center of Moscow, maximum CO concentrations of 28 mg/m^3 and 37 mg/m^3 were recorded on August 6th and 7th [Gorchakov et al., 2011; Zvyagintsev et al., 2011]. The MOPITT (Measurements of Pollution in the Troposphere) sensor flying on NASA's Terra satellite pointed out large plumes of high CO concentrations spreading all over western Russia early August (http://www.fire.uni-freiburg.de/GFMCnew/2010/08/09/20100809_ru.htm, accessed 2 July 2014).

Yurganov et al. [2011] estimated from ground-based and space-borne instruments that the total CO emitted by Russian fires was 34-40 Tg during July–August 2010. Using a CO inversion modeling technique implemented in a chemistry-transport model, Krol et al. [2013] provided an estimate of 22–27 Tg of CO for the region around Moscow between mid-July and mid-August. In comparison, all anthropogenic sources in Canada released about three to five times less CO (7.2 Tg) in 2010 (https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=94CC880D-1, accessed 10 September 2016).

PM_{10} and $PM_{2.5}$ concentrations are available for eight locations in the region of Moscow [van Donkelaar et al., 2011]. In July, averaged daily $PM_{2.5}$ concentrations were around 20-40 μg/m^3 at the suburban and urban sites (Figure 5). The smoke event in August increased concentrations by an order of magnitude. Both satellite-derived and in-situ $PM_{2.5}$ concentration datasets indicate a peak daily mean of about 600 μg/m^3 on August 7th.

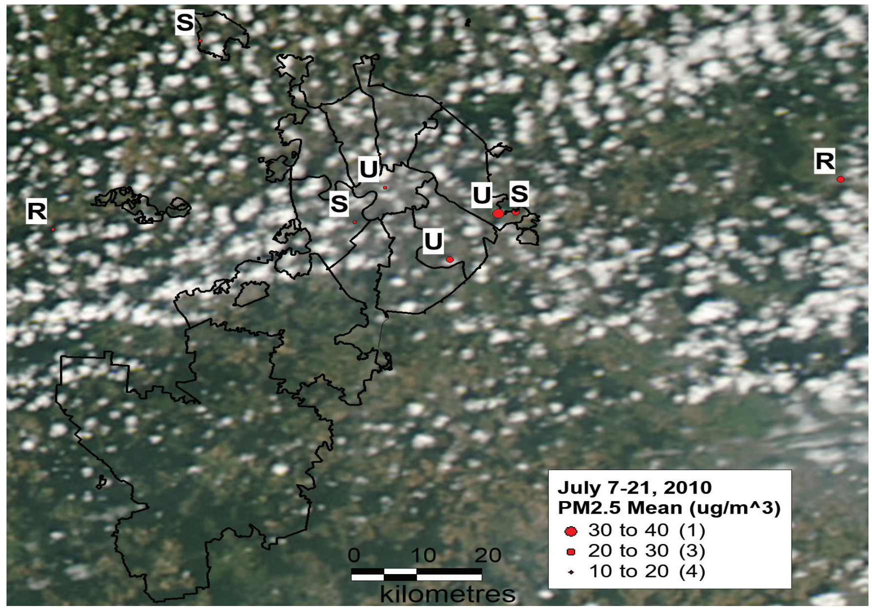
To assess the health effects of short-term exposure to PM from the fires, van Donkelaar et al. [2011] applied their $PM_{2.5}$ data sets to concentration-response relationships developed in studies of air pollution effects on human health. They concluded that exposure to the hazardous levels of atmospheric pollutants from the Western Russian fires may have caused hundreds of excess deaths in Moscow. Their estimates are in agreement with the figures provided by Goldammer [2010] in his report to the State Duma: "the average daily mortality rate of 350 to 380 [people] in Moscow almost doubled to about 700 [people] per day during the days of extreme heat and smoke pollution.". The reinsurance company Munich Re [2015] estimated that overall, 56,000 people died from the combined effect of the heat wave and dense smoke in 2010.

Modeling of Russian Smoke Plumes

The first objective of a modeling study was to be able to reproduce the high $PM_{2.5}$ concentrations by simulating the long-range transport of smoke plumes. A second goal was to understand how a few major fires (Figure 6) led to the poor air quality conditions in Moscow during the first week of August.

The fire and smoke modeling system applied to the major fires integrates five components in order to predict the effects of wildland fires on air quality (Figure 7). The first component is the Integrated Land Information System (ILIS) which was developed by the International Institute for Applied Systems Analysis [Shvidenko et al., 2011] to describe the physical and physiological characteristics of vegetation across Russian ecosystems. ILIS provided forest fuel loading data at a spatial resolution of 1 km in the simulation domain (Figure 6).

Secondly, the Fire Emission Prediction Simulator (FEPS) developed by the US Forest Service [Anderson et al., 2004] was applied to five large



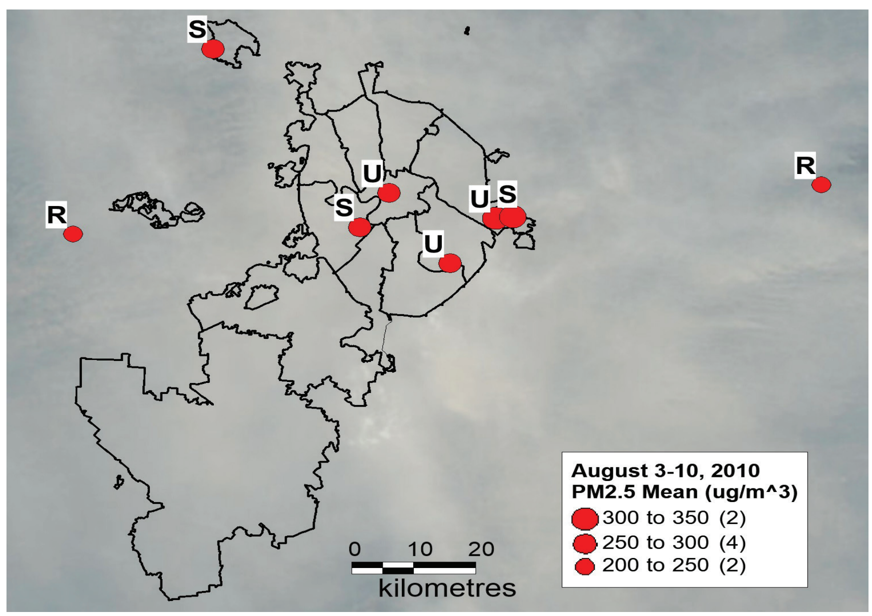


Figure 5: $PM_{2.5}$ concentrations measured in the Moscow region before (top) and during (bottom) the smoke event of 2010. Polygons represent the twelve administrative divisions ("okrugs") of the Russian capital (http://gis-lab.info/qa/moscow-atd.html, accessed 10 September 2016). The eight ambient air quality monitoring stations are classified as follows: urban (U), suburban (S) or rural background (R). MODIS Aqua scenes (250 m resolution) of the Moscow region show cloudy conditions on July 21st (top) and heavy smoke on August 7th (images courtesy of NOAA/NASA).

fires burning 200 km from Moscow during early August (Figure 6), using the vegetation and fuel loading information provided by ILIS. FEPS accounts for temperature and relative humidity to predict fuel consumption and atmospheric emissions on an hourly basis. $PM_{2.5}$ emissions and heat release are estimated for both flaming and smoldering phases.

Meteorological conditions over eastern Russia during August 3-10, 2010 were obtained using the Weather Research & Forecasting Model (WRF) (www.wrf-model.org, accessed 30 July 2016). WRF is the result of a collaborative partnership among various US organizations, principally the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA). WRF was first run at 36 km, and then successively nudged to 12 km and 4 km, the latter being used in our smoke simulation.

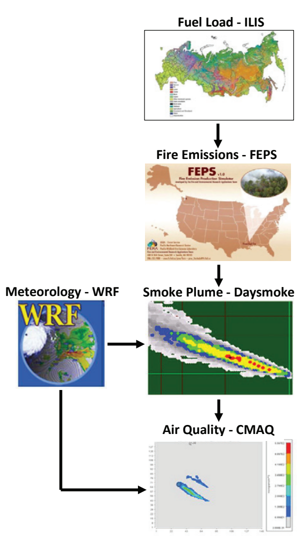


Figure 7: Overview of the five components of the wildland fire & smoke modeling system applied to the 2010 Russian fires.

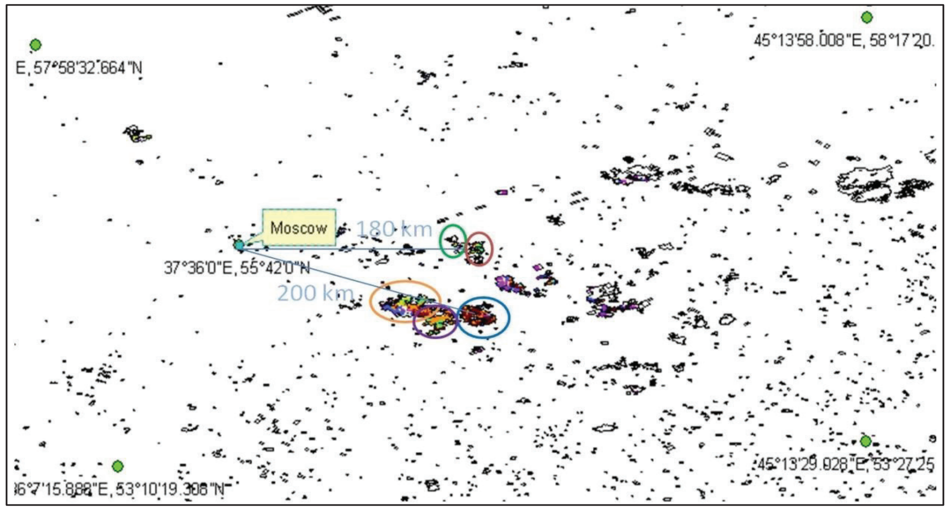


Figure 6: Location of the five major wildland fires whose smoke plumes affected Moscow's air quality during the first week of August 2010. The geographical boundaries of the CMAQ simulation domain are indicated by the four green dots.

The atmospheric dispersion of $PM_{2.5}$ emissions estimated with FEPS was simulated with the Lagrangian plume transport model Daysmoke developed by the US Forest Service [Achtemeier et al., 2011]. Daysmoke uses the meteorological data at the center of a selected fire (as calculated by WRF) in order to predict the trajectory of each air parcel representing 1 kg of $PM_{2.5}$,in a 2 km radius domain.

The effect on air quality was estimated with the Community Multi-scale Air Quality (CMAQ) modeling system (https://www.cmascenter.org/cmaq/, accessed 30 July 2016). CMAQ is an Eulerian chemical transport model which uses meteorological fields predicted by WRF. Plumes initially calculated with Daysmoke were assimilated in a 4 km x 4 km grid every 3 minutes. The simulation domain of 532 km x 604 km was centered on the five major fires close to the Moscow region (Figure 6). The domain included 131x151 cells horizontally and 34 vertical layers.

Simulations were performed from August 4th, 06:00 GMT to August 8th, 00:00 GMT. Because there are uncertainties associated with each of the models, different scenarios were set up to investigate the impact of fuel loading and plume heights on modelled concentrations at the surface.

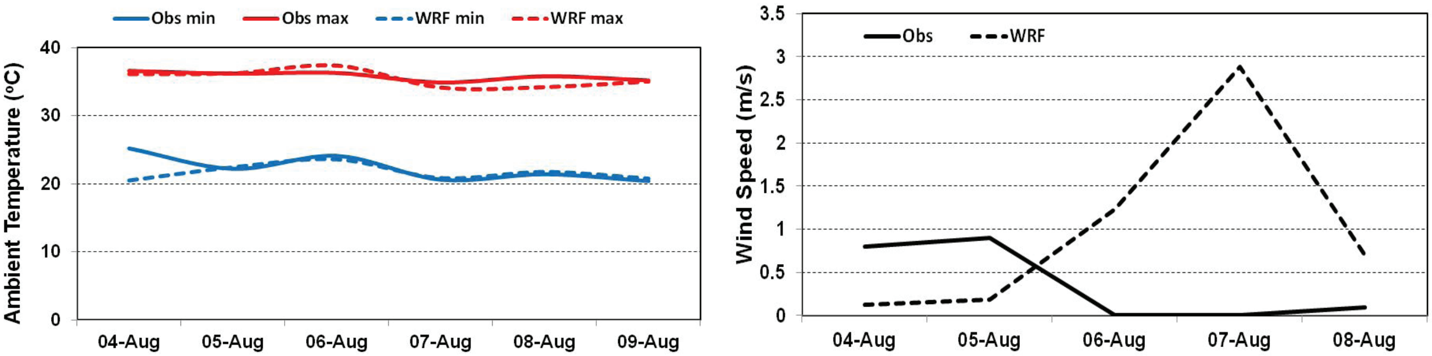


Figure 8: Comparison of surface (a) air temperatures and (b) wind speed observed and simulated with WRF at Moscow during early August 2010.

Comparison of Meteorological Model Outputs to Observed Weather

Temperatures and winds predicted with WRF were compared to meteorological observations at Moscow (Figure 8).

Daily maximum and minimum temperatures predicted with WRF are in agreement with observations at the Moscow VVC weather station. However, WRF overestimates wind speed when the atmosphere was stagnant over the region on August 6th and 7th.

Comparison of Modeled $PM_{2.5}$ Concentrations to Measurements

Both initial and boundary concentrations were set to zero in the CMAQ domain. Therefore simulations only show the effect of the fires on air quality. Results suggest that two major fires southeast of Moscow were the main contributors to high PM concentrations on August 7th. Figure 9 shows that a large plume hit the Russian capital after travelling more than 200 km, which is in agreement with satellite observations. In the Moscow region, modeled concentrations vary by as much as ~100 µg/m^3. Plumes from smaller fires east of the Russian capital disperse much faster and become part of background concentrations.

Because some simulation uncertainties are a result of characteristics of fire emissions implemented in the modeling system, sensitivity analysis on concentrations were conducted using different emission rates and plume heights.

Hourly $PM_{2.5}$ concentrations estimated between August 5th and August 8th with the original configuration (i.e., emissions from ILIS and plume heights from WRF) are shown in blue in Figure 10. Two other simulations were conducted using the same emission rates, but

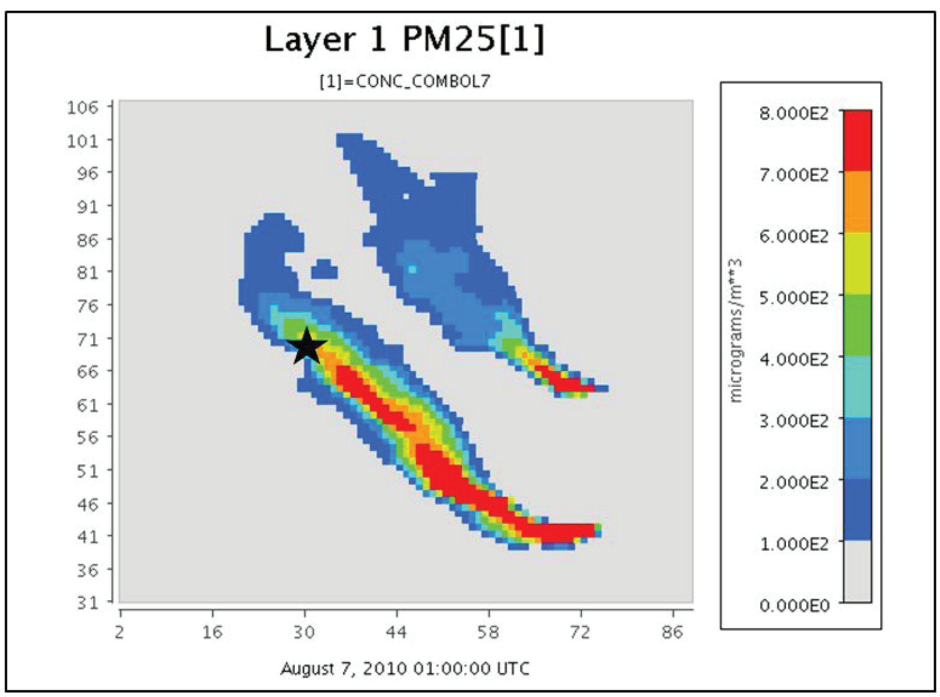


Figure 9: Modelled surface $PM_{2.5}$ concentrations on August 7th at 5:00 am local time (1:00 GMT). The location of Moscow is indicated with the black star.

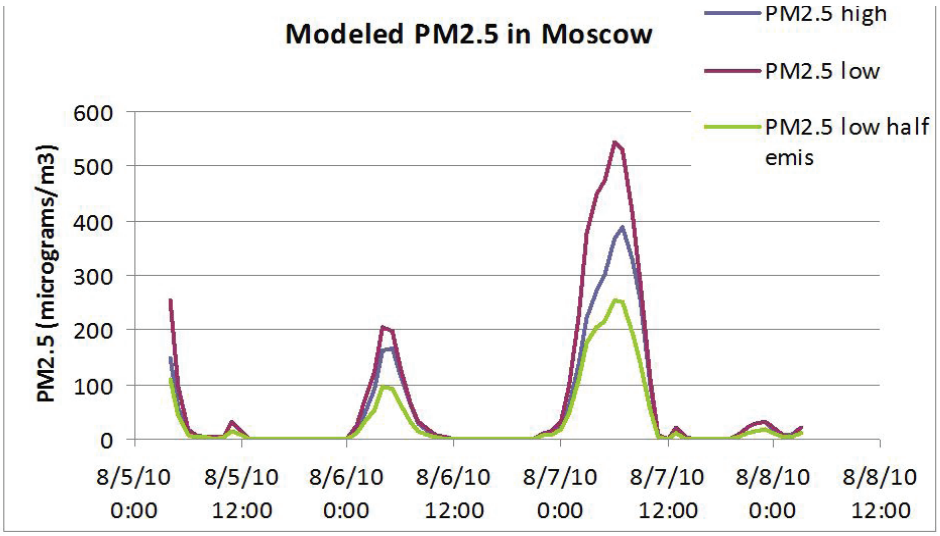


Figure 10: Hourly variation of $PM_{2.5}$ concentrations calculated at the Moscow location with three CMAQ runs using different emission scenarios. The blue color represents the concentrations calculated with the plume heights (primarily above the boundary layer) and emissions predicted with the modeling system; red denotes concentrations simulated with the predicted emissions, but injected closer to the surface (in the boundary layer); and green corresponds to half of the predicted emissions and injected closer to the ground.

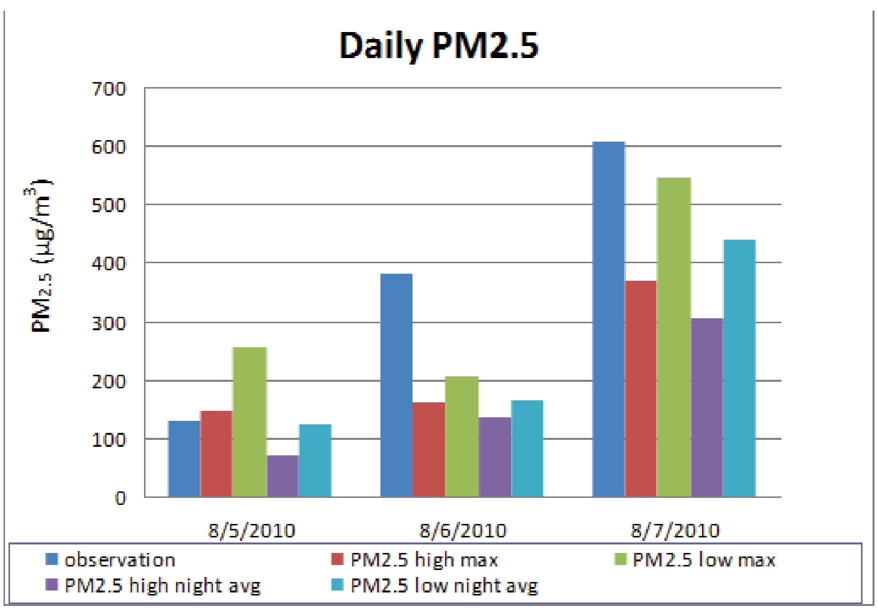


Figure 11: Comparison of $PM_{2.5}$ concentrations calculated with two different plume heights to observations (in dark blue) in Moscow. Red indicates the daily maximum modelled with WRF's boundary layer heights ("high") and green corresponds to daily maximum when plumes stay below 600 m ("low"). Nighttime averages are shown in purple for high plume injection and in light blue for lower injection.

injected closer to the ground (in red) and using half of the predicted emissions, also closer to the ground (in green). In all three simulations, concentrations peak at night when the boundary layer's height is at its minimum. As days go by, nighttime concentrations are increasing. According to the model, decreased emissions rates with shorter plume heights greatly reduce the impact on Moscow's air quality (see green line in figure 10).

Daily maximum and nighttime-averaged (midnight to sunrise) concentrations calculated with "high" and "low" plume heights were compared to $PM_{2.5}$ levels determined by Donkelaar et al. [2011] (Figure 11). Concentrations simulated with shorter plume heights are in better agreement with the atmospheric particulate level observed on August 7th. A "low" injection height reasonably reproduces the stagnant atmospheric conditions that were prevailing that day. On the other hand, simulation results suggest that plume heights did not greatly affect concentrations downwind on August 6th.

Conclusion

Five models were combined to predict the effect of wildland fires on air quality in downwind regions. The modeling system was applied to the Western Russian fires to predict Moscow's fine particulate atmospheric concentrations in early August 2010. Model outputs are in good agreement with measurements. Sensitivity analysis conducted with the modeling system demonstrated that emission rates, plume heights and atmospheric conditions are important factors to adequately reproduce high pollution levels caused by wildland fires.

Acknowledgements

We would like to thank Dr. Schepaschenko and Prof. Shvidenko from the International Institute for Applied Systems Analysis (Laxenburg, Austria) for their valuable collaboration on this project.

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"Connecting diverse wildland fire, emissions, air quality and modelling communities."

Comprehensive FireSmart® Implementation: More than Just Forest Fuel Management

by Kelly Johnston

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When most practitioners and local residents think FireSmart®, they likely think "fuel management", and more specifically "forest fuel management", but FireSmart is much more than forest fuel management. In fact, the FireSmart mission is to empower the public and increase community resilience to wildfire across Canada. In order to accomplish this the FireSmart concept involves addressing the full spectrum of wildland urban interface risk mitigation through helping communities become fire adapted and specifically, addressing the following seven FireSmart Disciplines:

1. Vegetation Management
2. Development
3. Public Education
4. Legislation
5. Interagency Cooperation
6. Cross Training
7. Emergency Planning

To help communities understand why it takes more than just forest fuel management to effectively mitigate wildland urban interface (WUI) losses, it's important to help them understand the factors that affect their vulnerability to wildfire. First, by providing them with the distinction between "wildland fire" and "wildfire" helps the public understand that wildland fire is an ecologically important natural disturbance of varying degree in most of our terrestrial ecosystems, and a wildland fire is termed a "wildfire" when it threatens to negatively impact the human values important to our society (primarily, natural resources, structures, infrastructure, human life, social and economic values) and becomes a WUI fire. It is also important for the public to understand that we have learned that we cannot effectively prevent the negative impacts of wildland fire on our values through suppression efforts alone. In fact, they should understand that the combination of our historical attempts to exclude fire from our ecosystems, expansion of development into wildland areas and the effects of climate change is resulting in an increase in WUI fire incidents and a decrease in the success of wildland fire suppression into the future.

With the increasing frequency of wildland urban interface fires, land managers and wildland fire agencies are responding with the best tools they have at their disposal: increased suppression efforts and wildland vegetation (fuel) management. By default, the wildland fire agencies have borne the brunt of "fixing" the WUI problem through fuel management alone, as this is publicly perceived to be the root of all the WUI problems; hence "FireSmart" is largely perceived as "fuel management" and fuel management alone.

To dispel this perception, we should first start with what actually "fuels" a WUI fire. Wildland vegetation (organic layers, surface grasses and forbs, shrubs and trees, etc.) provides fuel for wildland fires, allowing fire to spread from one point of ignition to another through the radiant, convection, or conduction heat transfer processes. Fires advance via the main flaming front or the ignition of receptive fuels well ahead of the main fire via embers. These same transfer of heat mechanisms occur when a fire transitions from these wildland fuels to structures and infrastructure. The primary vector of heat transfer and subsequent fire spread from wildland fuels to structures (and vice versa) is ember transport. A number of research and case studies document ember transport and ignition of receptive fuels from several meters to several kilometres ahead of fire. Based on this, we can then help the public understand that these structures should be considered fuel as well. After all, they are essentially trees milled into dimensional lumber, rearranged and often supplemented with hydro-carbon based products (vinyl siding, vinyl gutters, plastic patio furniture with foam cushions..etc.). This creates a combined fuel complex of wildland fuels (vegetation) and built fuels (structures and infrastructures) and allows us to redefine the wildland interface as "Any developed area where conditions affecting the combustibility of both wildland and built fuels allow for the ignition and spread of fire through the combined fuel complex".

Once ignition of these

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built fuels occurs, fire spreads to neighbouring receptive built fuels (structure to structure) and vegetation in the same manner as it spreads through the wildland fuels. This typically becomes known as an urban conflagration (independent of the periphery wildland fire) which often and swiftly overwhelms the capabilities of urban fire resources.

In the same way that wildland fuels can be modified to influence fire behaviour, built fuels can also be modified to be more ignition resistant. By providing the public with a general understanding of the role of wildland fire and the wildland urban interface fire environment, we can demonstrate that FireSmart is not just vegetation management, and is not just the responsibility of wildland fire managers, but requires a larger perspective that encompasses the other six FireSmart Disciplines:

- **Development** - educating and empowering land use planners to create appropriately planned communities where access, egress, structure density, set-backs and other issues are addressed
- **Public Education** - engaging and empowering community leaders and the public to take action on their private lands through the FireSmart Community Recognition Program
- **Legislation** - strengthening of building code and other local government regulations that require the inclusion of FireSmart best practices
- **Interagency Cooperation** - the cooperation between all land-management emergency response agencies to ensure a comprehensive and collaborative approach to addressing the complex WUI challenge
- **Cross Training** - training of land management and emergency response staff at all levels of government to increase the effectiveness of cross-jurisdictional mitigation and emergency response efforts
- **Emergency Planning** - interagency and inter-jurisdictional plan mitigation and emergency planning focused on community fire adaptation and resiliency.

Mitigating the structure and infrastructure loss potential to WUI fire through the application of a comprehensive and collaborative FireSmart program, incorporating all seven FireSmart disciplines will not only reduce the resulting negative social, economic and health impacts, but will allow more options for the appropriate role of wildland fire in our terrestrial ecosystems. This will ultimately allow governments at all levels to engage, support and empower communities and the public in becoming fire adapted and, ultimately fire resilient using FireSmart tools.

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"Connecting diverse wildland fire, emissions, air quality and modelling communities."

FireWork – A Canadian Operational Air Quality Forecast Model with Near-Real-Time Biomass Burning Emissions

by Radenko Pavlovic[1], Jack Chen[2], Didier Davignon[1], Michael D. Moran[2], Paul-André Beaulieu[1], Hugo Landry[1], Mourad Sassi[1], Samuel Gilbert[1], Rodrigo Munoz-Alpizar[1], Kerry Anderson[3], Peter Englefield[3], Susan M. O'Neill[4], Narasimhan K. Larkin[4], Jacinthe Racine[1], Sophie Cousineau[1], Sylvain Ménard[1], Alain Malo[5], Jean-Philippe Gauthier[5], Nils Ek[5], Guillaume Marcotte[5], Pierre Bourgouin[5] and Véronique Bouchet[5]

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Environment and Climate Change Canada's (ECCC) North American air quality (AQ) forecast system with near-real-time (NRT) wildfire emissions, named FireWork, was developed in 2012. From 2013 to 2015, the system was run in experimental mode at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP), where FireWork forecasts were made available to ECCC forecasters and interested external users. The system became operational in April 2016, and for the first time in the department's history, air quality model forecasts of the impacts of wildfire events were made available to the general public. This article will introduce the current FireWork operational system and provide information and examples of model products that are available to air quality forecasters and emergency first-responders. For details on model science and performance evaluation, readers are referred to Pavlovic et al. (2016).

The FireWork system was built by ECCC in collaboration with the Canadian Forest Service and with contributions from the U.S. Forest Service. In the current operational setup, the system is run twice daily from April 1st to November 1st with model initializations at 00UTC and 12UTC to produce numerical AQ forecasts over North America with a 48-hour lead time. The FireWork domain covers almost all of Canada and most of the continental U.S., including Alaska (Figure 1).

During the period from 2014 to 2016, we witnessed very intense wildfires raging in northwestern Canada. In June and July of 2014, the Northwest Territories (NWT), especially the Yellowknife region, experienced many large fires. Smoke from these wildfires reached eastern Canada and the eastern U.S., and was even observed as far away as Portugal (NP, 2014). In terms of total area burned, the 2015 fire season was the 6th most intense wildfire season in the past 33 years according to the Canadian Interagency Forest Fire Centre (CIFFC, 2015). Finally, the 2016 fire season included unprecedented impacts on both people and the economy, when the entire city of Fort McMurray, Alberta, with a population of 80,000, was evacuated in May as it was being overrun by a large, fast-moving wildfire. Estimated insured fire damages to Fort McMurray were 3.6 billion dollars, the costliest insured natural disaster in Canadian history (IBC, 2016).

In addition to direct property damage, wildfires also produce large amount of pollutants that can be transported long distances and cause large health-related impacts in communities downwind. Figure 2 shows the average impact of wildfires which occurred during the summers of 2014 and 2015, expressed as their contribution to summertime average surface $PM_{2.5}$ concentrations as forecasted by FireWork. The modelled average wildfire contribution to $PM_{2.5}$ reached 30 $\mu g/m^3$ across many regions in western Canada and the western U.S.

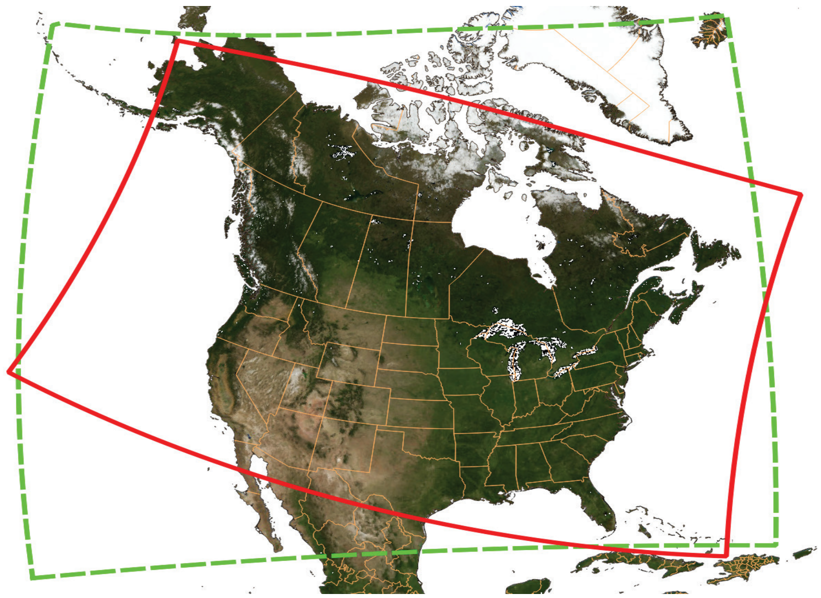

Figure 1: FireWork domain boundaries prior to (red) and post (green) September 7th 2016.

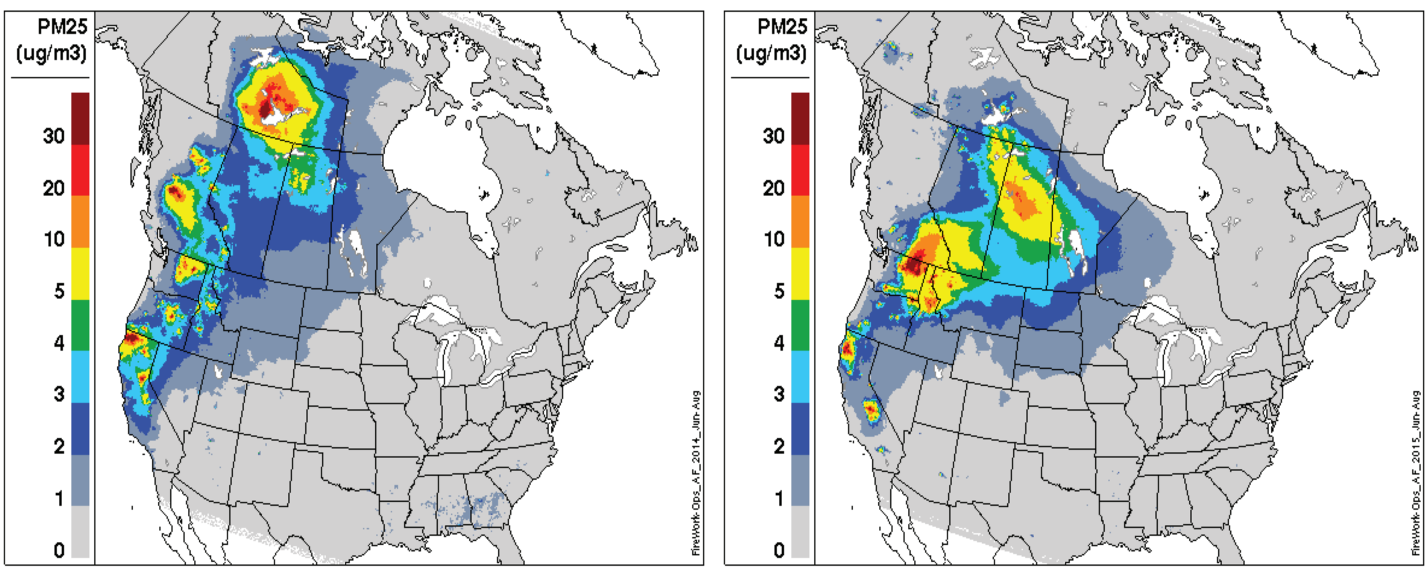

Figure 2: Forecasted summertime (June-August) 2014 (left) and 2015 (right) wildfire emissions contribution to 3-month average one-hour surface $PM_{2.5}$ concentrations (μg/m^3).

FireWork System Description

The FireWork system is identical to the ECCC Regional Air Quality Deterministic Prediction System (RAQDPS) except for the inclusion of biomass burning emissions. The RAQDPS is ECCC's operational numerical regional AQ forecasting system (Moran et al., 2012, 2015; Im et al., 2015). The RAQDPS uses a rotated latitude-longitude grid with 10 km horizontal grid spacing and 80 vertical levels, from the surface up to 0.1 hPa. The heart of the RAQDPS is the GEM-MACH model, an on-line, one-way-coupled chemical transport model

(CTM) embedded within the Global Environmental Multi-scale numerical weather prediction model (GEM) (Côté et al., 1998a,b; Charron et al., 2012). The current version of the RAQDPS uses hourly emissions based on the 2010 Canadian national criteria-air-contaminant (CAC) anthropogenic emissions inventory, the 2011 U.S. National Emissions Inventory (NEI), and the 1999 Mexican emissions inventory as well as biogenic and sea-salt emissions from natural sources (Moran et al., 2015).

As FireWork and the RAQDPS are nearly identical systems, differing only in the inclusion of wildfire emissions in FireWork, a subtraction of RAQDPS pollutant forecast fields from FireWork fields provides an estimate of wildfire emission contributions on total forecasted pollution. This simple strategy, although computationally expensive, allows the location and behaviour of wildfire smoke plumes to be isolated, followed, and forecasted. From a forecaster's perspective, having both RAQDPS and FireWork forecasts available is also preferable, as the evolution of fire emissions is highly uncertain.

The FireWork modelling system framework and data flow are presented in Figure 3. The initial information on near-real-time (NRT) biomass burning from both Canada and the U.S. is provided by the Canadian Wildland Fire Information System (CWFIS) operated by the Canadian Forest Service, Natural Resources Canada (NRCan) (http://cwfis.cfs.nrcan.gc.ca; Lee et al., 2002).

The CWFIS is an operational fire information system that monitors fire danger conditions across Canada following the Canadian Forest Fire Danger Rating System (Stocks et al., 1989). Daily noon weather conditions are collected from over 2500 federal and provincial weather stations, which are used to calculate daily Canadian Forest Fire Weather Index (FWI) System indices. The CWFIS also maintains a national forest fuels map based on national and regional forest inventory databases. Forest fuel and interpolated FWI indices are used by the Canadian Forest Fire Behaviour Prediction (FBP) System to calculate potential fire behaviour and fuel consumption.

The CWFIS uses observations from the U.S. National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) and the U.S. National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite-based detection systems to detect current wildland fires (Anderson et al., 2009), commonly referred to as hotspots. Fuel consumption in tonnes per hectare is estimated at observed hotspot locations and passed on to FireWork.

Once the initial fuel consumption estimates are available from CWFIS, a component of the U.S. Department of Agriculture (USDA) Forest Service BlueSky smoke modelling framework (Larkin et al., 2009) is used to calculate daily total emissions for each fire hotspot. BlueSky is a modelling framework that aggregates independent models of meteorology, fire activity (e.g., location and size), fuel loads, fuel consumption, diurnal allocation of fuel consumption and emissions, vertical allocation of emissions (e.g., plume rise) and dispersion or air quality models to estimate hourly $PM_{2.5}$ emissions and hourly surface concentrations of $PM_{2.5}$ from wildland fires. The Fire Emission Production Simulator (FEPS) module of BlueSky is invoked in the FireWork processing and is part of an interagency effort to cooperate on sharing of data and methodologies.

The Sparse Matrix Operator Kernel Emissions (SMOKE) emissions processing software (CEP, 2012) is then used to convert the daily emissions into hourly values and into explicit modelled species for each hotspot. Finally, these hourly wildfire emissions are merged with anthropogenic point-source emissions and are input to the GEM-MACH model.

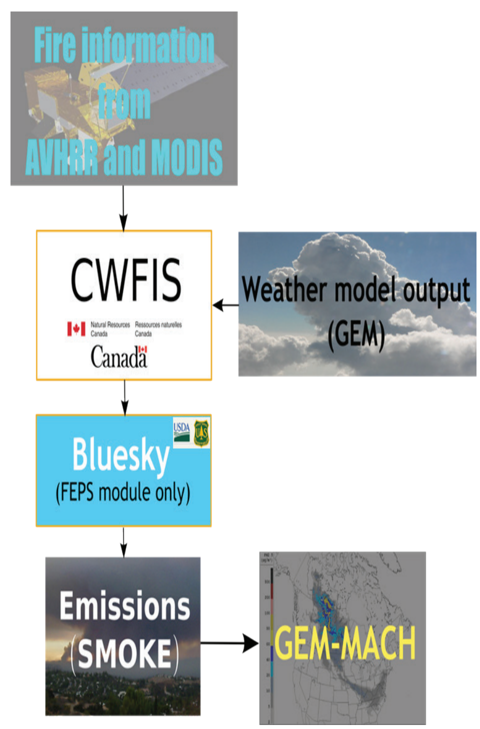

Figure 3: FireWork model system framework and data flow

FireWork Products and Dissemination

FireWork forecasts and products have been available to ECCC operational forecasters via an internal web page since 2013. In 2016, with the system becoming fully operational at CCMEP, key products were made available to the public as part of the Government of Canada weather information website (ECCC Analyses and Modelling website: https://weather.gc.ca/firework; and the ECCC Geospatial Web Services website: http://www.ec.gc.ca/meteo-weather/default.asp?n=C0D9B3D8-1). A special password-protected web page (http://collaboration.cmc.ec.gc.ca/cmc/air/firework) with additional FireWork AQ products is also available to emergency responders.

Government of Canada weather information websites

ECCC Analyses and Modelling website

Since May 2016, the following FireWork $PM_{2.5}$-related products have been available on the ECCC public-access Analyses and Modelling web page (https://weather.gc.ca/firework/):

(i) hourly $PM_{2.5}$ surface-level concentration maps and animations [0-48 h];
(ii) hourly $PM_{2.5}$ total column maps and animations [0-48 h];
(iii) 24-hour average $PM_{2.5}$ surface-level concentration map [first 24 h].

These products are available for the two most recent model runs, initialized at 00 UTC and 12UTC, and results are generally available around 0530 UTC and 1700 UTC, respectively. A subtraction of RAQDPS fields from FireWork fields is applied to determine the wildfire emission contributions to total forecasted $PM_{2.5}$ levels across the model domain. The total column concentrations are calculated as a an integral over a column of the atmosphere, and represent column aerosol loading as result of wildfire emission contribution to each model grid cell. Examples of some of the FireWork products available on this web page are presented in Figure 4.

In addition to forecast $PM_{2.5}$ concentration fields, other useful information and links (about the FireWork system, the impact of wildfire smoke on air quality and health, Canadian Air Quality Health Index (AQHI) values, etc.) are also provided on this web page.

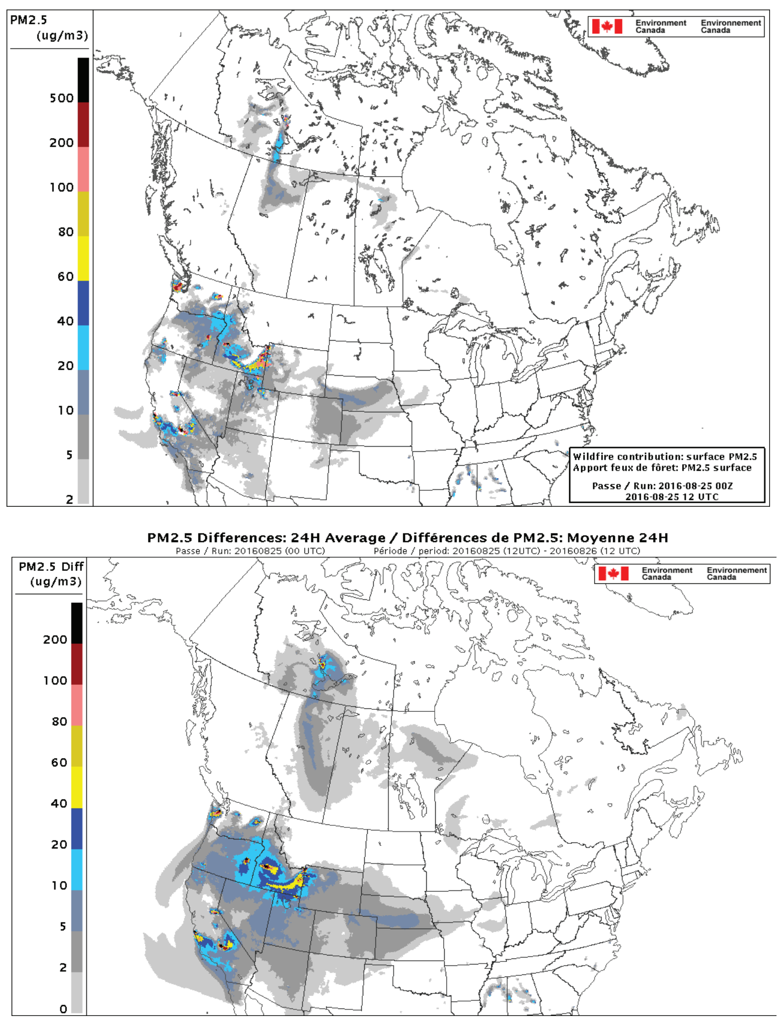

Figure 4: Forecasted wildfire emissions contribution to surface $PM_{2.5}$ concentrations ($\mu g/m^3$) valid at 2016-08-25 12UTC (top) and averaged over 24 hours (2016-08-25 12UTC to 2016-08-26 12UTC) (bottom) forecasted by 2016-08-25 00UTC run.

"Connecting diverse wildland fire, emissions, air quality and modelling communities."

ECCC Geospatial Web Services

The ECCC GeoMet project provides access to ECCC raw numerical-weather-prediction (NWP) model and air-quality-forecast-model output data layers (http://www.ec.gc.ca/meteo-weather/default.asp?n=C0D9B3D8-1) via two Open Geospatial Consortium web service standards: Web Map Service (WMS) and Keyhole Markup Language (KML).

Meteorological layers are dynamically served through the WMS standard to enable end-users to display meteorological data with their own tools and on interactive web maps. They are also served through the KML standard for easy display in tools such as Google Earth™.

With respect to model layers from FireWork, $PM_{2.5}$ and PM_{10} fields attributed to wildfires are available for the surface level and as sums over an atmospheric column. Screenshots of these products shown in Google Earth™ software are presented in Figure 5.

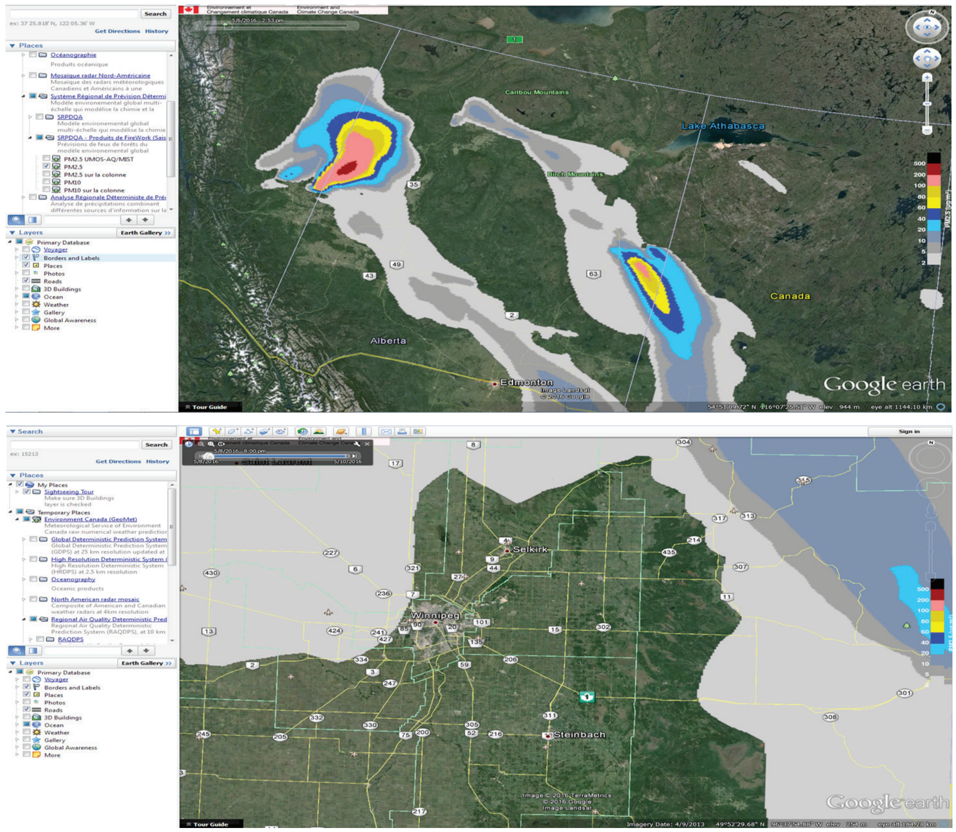

Figure 5: Forecasted wildfire emissions contribution to surface $PM_{2.5}$ concentrations (μg/m^3) valid at 2016-05-06 12UTC as forecasted by the 2016-05-06 00UTC FireWork run (upper image), and a close-up of the surface $PM_{2.5}$ concentration field two days later over southern Manitoba valid at 2016-05-08 20UTC as forecasted by the 2016-05-08 00UTC run (lower image). These examples were produced using ECCC Geospatial Web Services and displayed using the Google Earth™ program.

FireWork password-protected web page

This web page is prepared for FireWork users needing additional information about current wildfires and areas affected by related pollution over North America. This page is password-protected and can be accessed through http://collaboration.cmc.ec.gc.ca/cmc/air/firework/. As of August 2016, the page has over 100 subscribers.

For those interested in this special FireWork web page, an access request can be sent to firework@ec.gc.ca. Presently, access is granted under certain conditions to academics, government agencies, and emergency first responders. Examples of FireWork products related to $PM_{2.5}$ and PM_{10} that are available on this page are:

(i) Surface-level and total column $PM_{2.5}$ attributed to wildfire emissions

a. Surface-level maps and animations [0-48 forecast hour]
b. Surface-level average maps over 24h [0-24 h]
c. Surface-level average maps over 48h [0-48 h]
d. Surface-level maximum values map over 48 h
e. Total column maps and animations [0-48 h]

Examples of four of these $PM_{2.5}$ products are presented in Figure 6.

(ii) Surface-level and total column PM_{10} attributed to wildfire emissions

a. Surface-level maps and animations [0-48 h]
b. Total column maps and animation [0-48 h]

(iii) Maps of surface-level PM2.5 concentrations with UMOS-AQ/MIST correction applied to the non-wildfire-related $PM_{2.5}$ concentration field

One of the RAQDPS standard post-processing products comes from the Updateable Model Output Statistics for Air Quality (UMOS-AQ) package. The UMOS-AQ package applies statistics for bias correction to compensate for systematic AQ model errors and to account for unresolved subgrid-scale phenomena at locations of air quality measurement stations in Canada (Wilson and Vallée, 2002, 2003; Antonopoulos et al., 2010; Moran et al., 2012). Hourly RAQDPS forecasts of pollutant concentrations and meteorological quantities at these measurement locations are combined with available hourly surface measurements to statistically adjust and regenerate location-specific hourly forecasts. The UMOS-AQ location-specific O_3, $PM_{2.5}$, and NO_2 concentrations are the quantities used in the calculation of the AQHI values that are provided to local forecasters and disseminated to the public. The acronym MIST stands for "Moteur d'Interpolation STatistique, an ECCC statistical interpolation package that uses the optimal-interpolation algorithm described by Mahfouf et al. (2007) to interpolate UMOS-AQ predictions to locations without AQ measurement stations.

In the case of FireWork, the UMOS-AQ/MIST RAQDPS results are incremented with the $PM_{2.5}$ wildfire emission contribution

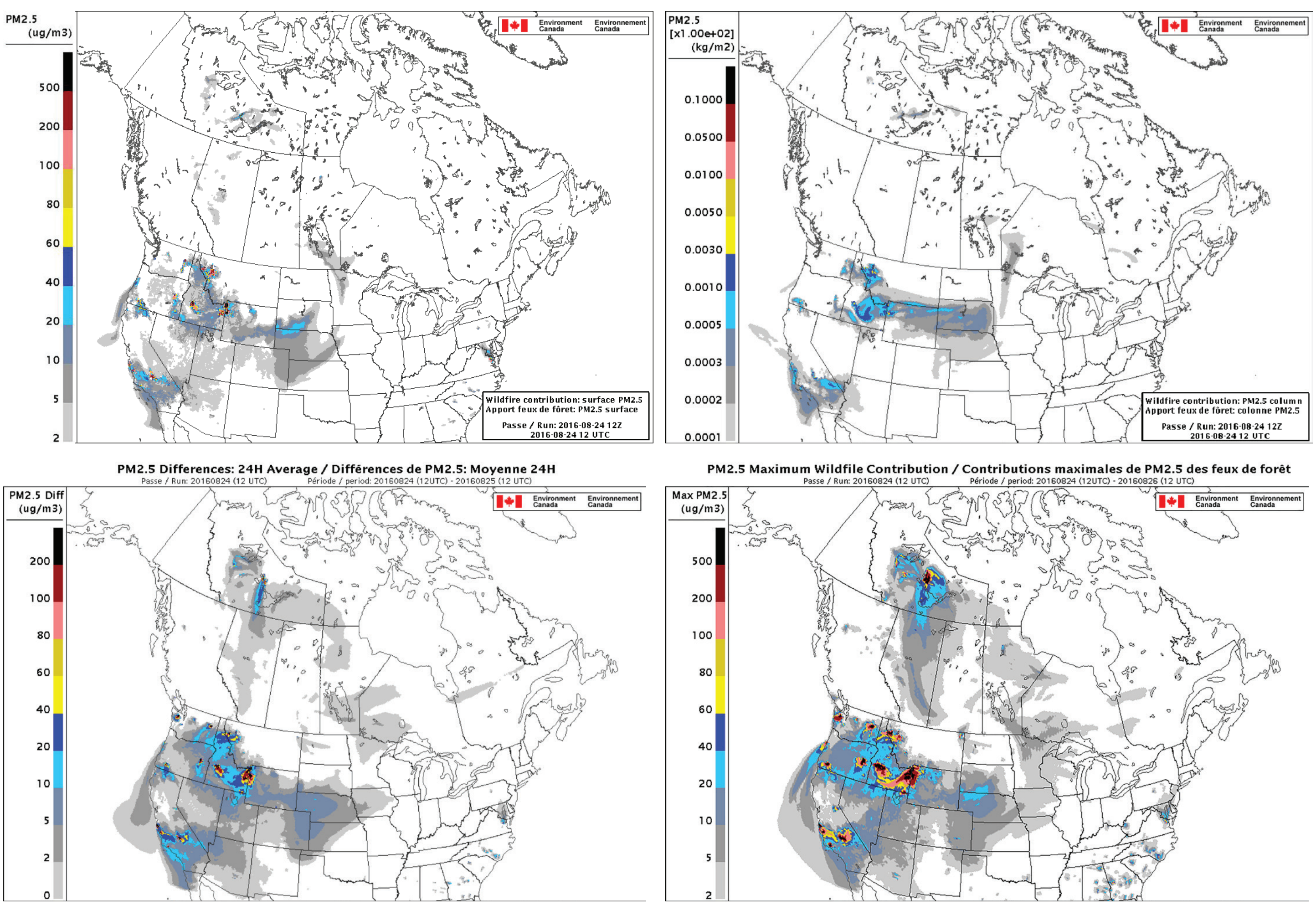

Figure 6: Examples of FireWork forecasts of wildfire emissions contributions to $PM_{2.5}$ concentrations (µg/m^3) at surface level (upper-left panel), for total column (upper-right panel), averaged over 24 hours (lower-left panel), and maximum hourly values over 24 hours (lower-right panel). These examples are forecasted by the 2016-08-24 12UTC run.

as modelled by FireWork. The example of this product is presented in Figure 7. Since statistical bias corrections are driven mostly by local meteorological conditions and do not account for unusual AQ events such as wildfires, adding the FireWork $PM_{2.5}$ concentration field from wildfire contributions on top of the UMOS-AQ/MIST non-wildfire $PM_{2.5}$ adjusted forecast results improves forecast accuracy while keeping the influence of $PM_{2.5}$ contributed by wildfire emissions. These statistically-adjusted $PM_{2.5}$ results, along with the objective analyses presented in the next section, provide information on total surface $PM_{2.5}$ concentrations, not only wildfire-related $PM_{2.5}$, which is more relevant for local forecasters and first responders.

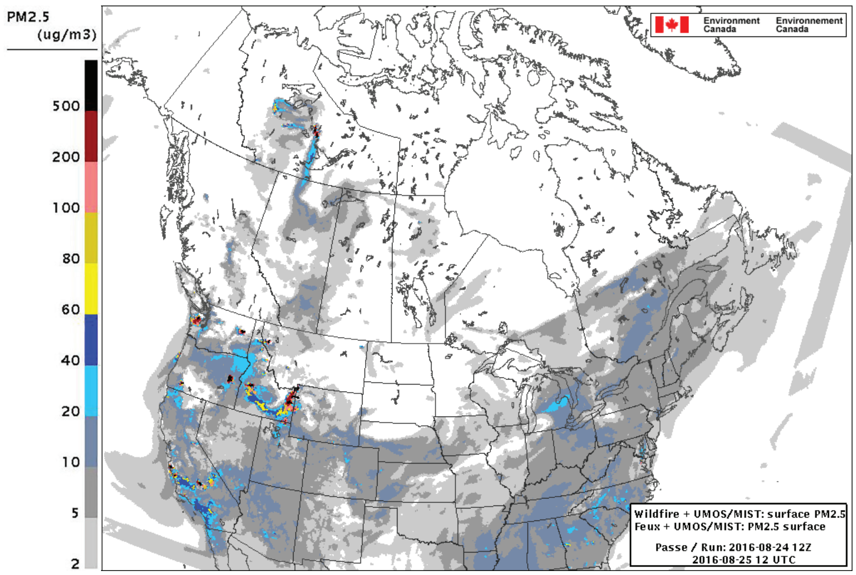

Figure 7: Examples of the post-processed UMOS-AQ/MIST $PM_{2.5}$ concentration field (µg/m^3) based on by 2016-08-24 12UTC FireWork run and valid at 2016-08-25 12UTC.

(iv) Hourly objective analyses for $PM_{2.5}$ and PM_{10} based on FireWork output (RDAQA-FW)

In order to better quantify current pollutant concentrations at the surface, FireWork was also connected to ECCC's Regional Deterministic Air Quality Analysis (RDAQA) post-processing package (Robichaud and Ménard, 2014). Pollutant concentration fields predicted by FireWork are used as first-guess fields by this package together with Canadian and U.S. surface AQ measurements to generate objective analyses (OA) of hourly North American pollutant surface concentration fields. The FireWork version of the RDAQA, named RDAQA-FW, uses a combination of AQ measurements and gridded FireWork forecast fields. NRT objective analyses, available for each analyzed hour with an approximately 2 hour delay, are currently available from RDAQA-FW for two pollutants ($PM_{2.5}$ and PM_{10}). Surface objective analyses are an important addition to the suite of numerical air quality guidance that is used to assist regional forecasters, as they provide a visual indication of recent model performance.

Figure 8 shows results for one interesting case on 9 July 2014, where the difference between the FireWork $PM_{2.5}$ forecast and the companion RDAQA-FW analysis that followed was important. In July 2014 there were very intense wildfires burning near Yellowknife, NWT. Smoke from these wildfires was advected to southern Manitoba, northeastern Montana, and North Dakota. In this particular case, FireWork under-predicted both $PM_{2.5}$ surface concentrations and the spatial extent of the plume, but operational AQ forecasters were able to adjust local forecasts as RDAQA-FW results became available that showed much higher $PM_{2.5}$ concentrations that would be transported downwind over time. Overall, RDAQA-FW has been found to be very useful since it allows operational AQ forecasters to adjust, if necessary, FireWork forecasts when long-range wildfire pollution transport is present.

(v) Interactive FireWork Webmaps

FireWork's Webmap tool enables interactive viewing of predicted wildfire smoke plumes and satellite-detected hotspots. The user interface is a Web application built with a modified version of OpenLayers that adds time-based animations. It allows the display of multiple geospatial layers with zooming and panning. Furthermore, Permalink features allow direct access to a specific frame and zoom.

Users can toggle the display of hotspots on the map and overlay

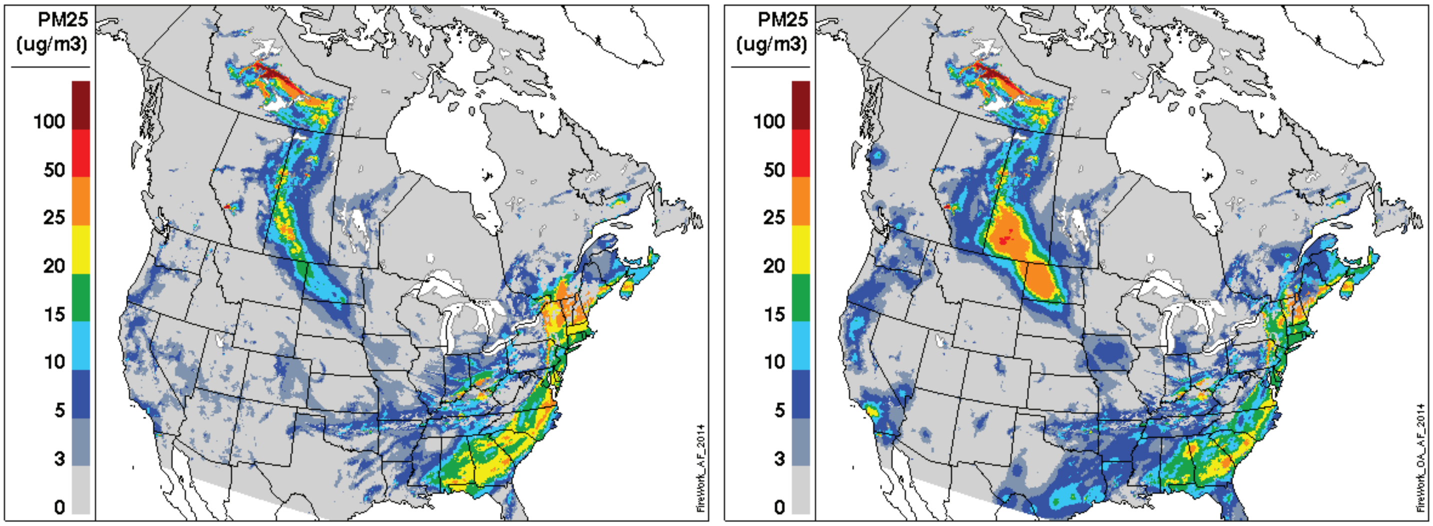

Figure 8: $PM_{2.5}$ surface concentrations on 9 July 2014 forecasted by FireWork (left) and adjusted by RDAQA FW (right).

the modelled $PM_{2.5}$ surface or column total concentrations from FireWork. This feature is based on a development version of ECCC's new GeoMet platform via the WMS standard. A hotspots layer is included, derived from FireWork's preprocessor, thus ensuring that only sources considered by FireWork are shown in the Webmap. Two examples of interactive FireWork Webmaps are presented in Figure 9.

(vi) Wildfire Event-Specific Products

When a major wildfire event occurs within the FireWork model domain, ECCC is able to rapidly provide additional wildfire-related AQ pollution products to FireWork users upon request. For the most recent wildfire season (summer 2016) several specialized products were made available for the areas affected by wildfires in the vicinity of Fort McMurray, Alberta.

As default FireWork product images are continental, additional images zoomed over affected areas are produced in the operational setup for the duration of some wildfire events. The type and number of the additional

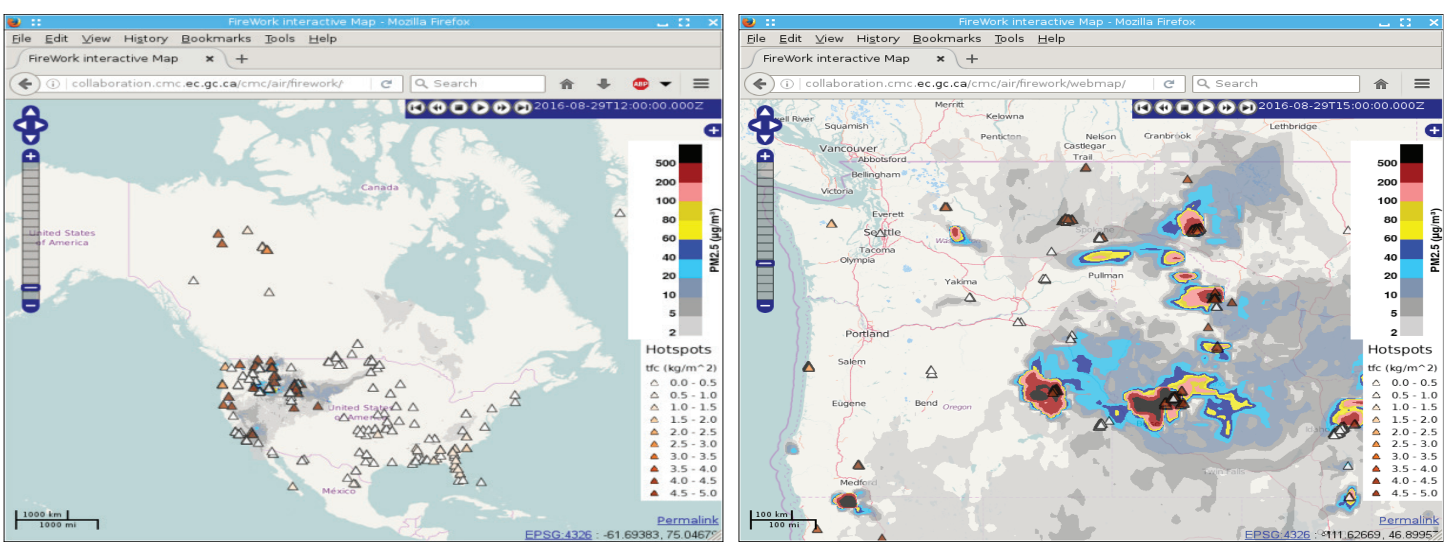

Figure 9: Examples of the interactive FireWork webmaps over the FireWork domain (left) and zoomed over the western U.S. and Canada (right) showing Total Fuel Consumption (TFC) values representing flaming combustion (kg/m²), and the contribution of forecasted wildfire emissions to $PM_{2.5}$ surface concentrations (µg/m³), valid at 2016-08-29 12UTC (left) and 15UTC (right) from the 2016-08-29 12UTC FireWork run.

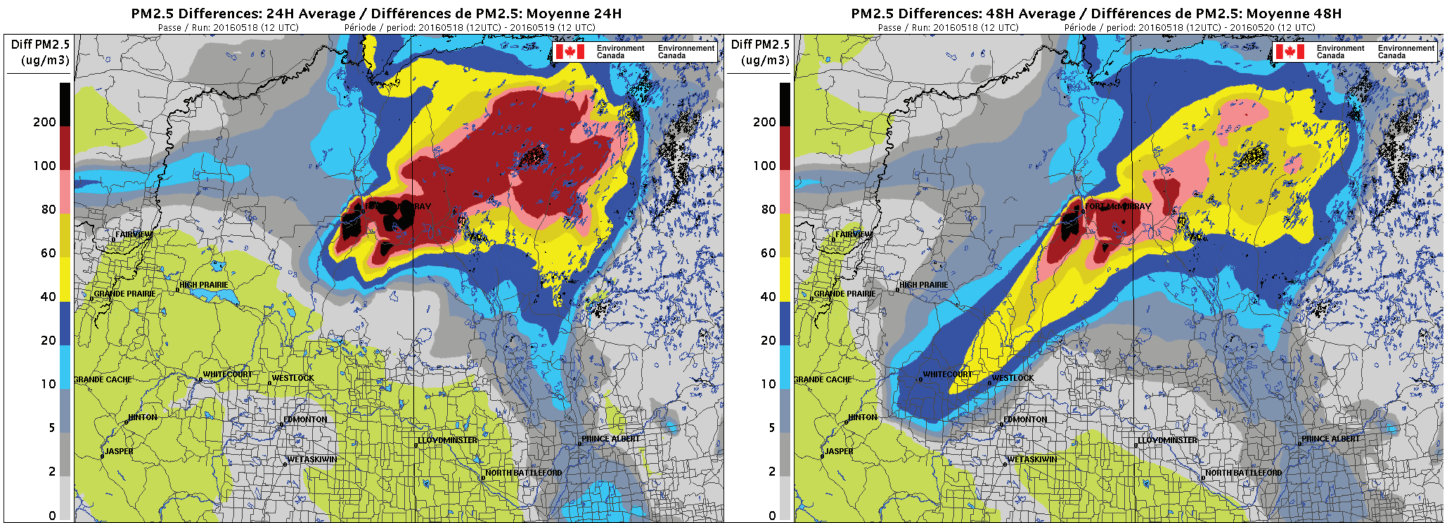

Figure 10: Examples of the FireWork products prepared for the May 2016 Fort McMurray wildfire event in northern Alberta, showing the forecasted wildfire emissions contribution to surface $PM_{2.5}$ concentrations (µg/m3) over a 24-hour period (left) and a 48-hour period (right). These examples were both produced by the 2016-05-18 12 UTC run.

wildfire-emissions related products depend on the nature of the individual wildfire event and on user demand and can vary from one case to another. Some examples of additional products prepared for the Fort McMurray wildfire event are presented in Figure 10.

(vii) Client-Specific Products

ECCC tries to accommodate different types of requests from users looking for data and products from the FireWork system. Some of these products are delivered and shared via the FireWork password-protected web page

In addition, ECCC can establish custom operational data feeds for FireWork or other data sets through contractual agreements, with cost-recovery service charges.

2016 Fort McMurray Wildfire Event

The 2016 Canadian wildfire season was certainly notable for the intense wildfires which burned part of the city of Fort McMurray in May, causing the evacuation of 88,000 people (CBC, 2016). Although the FireWork system, with its 10 km horizontal resolution, is not designed to address urban interface wildfire response, special AQ products were made available for this event.

Figure 11 shows the forecasted wildfire emissions contribution to the average surface $PM_{2.5}$ concentrations in northern Alberta and Saskatchewan for the month of May. For the area close to Fort McMurray the average forecasted wildfire contributions to total forecasted $PM_{2.5}$ concentrations for all of May were above 50 µg/m^3. Based on the maximum hourly concentrations, almost half of northern Alberta and Saskatchewan had forecasted hourly $PM_{2.5}$ values above 100 µg/m^3. In particular, the area close to Fort McMurray and few hundred kilometers downwind of the city had forecasted maximum concentrations well above 500 µg/m^3 and the most heavily affected area had forecast values above 10,000 µg/m^3.

Related ECCC Emergency Response Tools

Wildfires can pose a health threat for population living in their vicinity. In addition to the catastrophic forest fires in Fort McMurray this year, a similar situation occurred with the major forest fires in Haute-Mauricie (La Tuque, Quebec) in May-June 2010, the forest fires near Timmins and Kirkland Lake (Ontario) in May 2012 and most recently in Kejimkujik National Park (Nova Scotia) in August 2016. In emergency situations like these, the Environmental Emergency Response Section (EERS) of CCMEP can be contacted to obtain immediate assistance and expertise in atmospheric transport and dispersion modelling. EERS operates on a 24/7 basis for any emergency response involving natural or anthropogenic releases into the

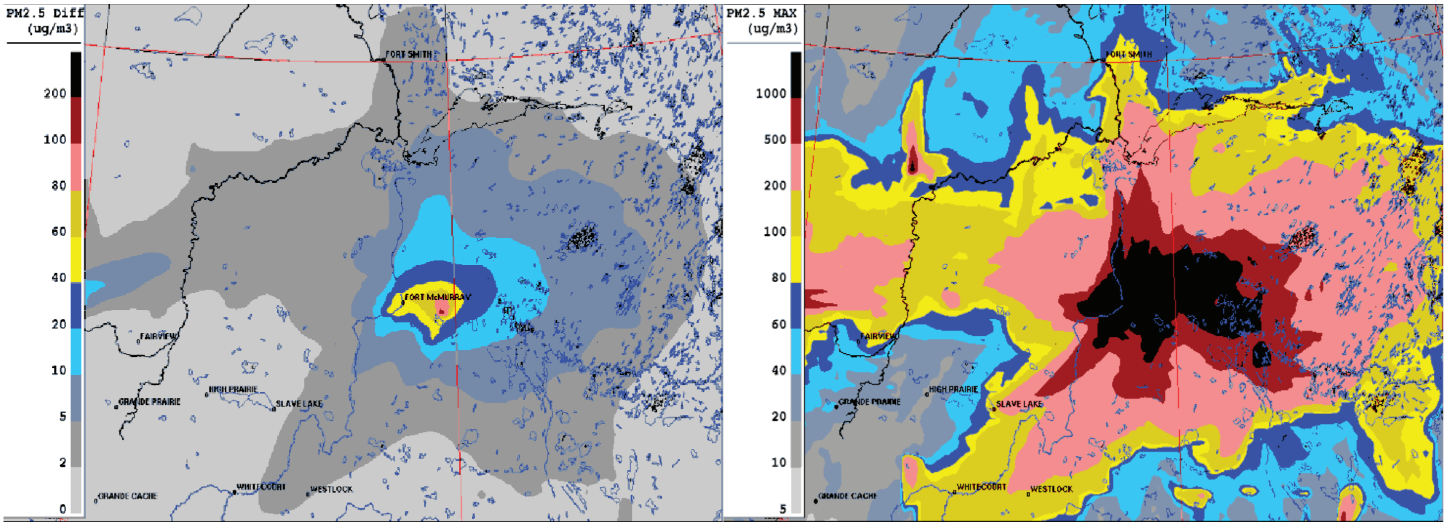

Figure 11: Forecasted wildfire emissions contribution to mean monthly $PM_{2.5}$ concentrations at the surface (left) and to maximum hourly $PM_{2.5}$ concentrations (µg/m³) forecasted by FireWork (right) for May 2016.

atmosphere of chemical, biological, radiological, nuclear (CBRN) substances, smoke from forest fires and landfill sites, or volcanic ash. EERS provides a response to various federal, provincial and municipal partners and stakeholders within 90 minutes of initial notification. EERS can be contacted through different channels of ECCC depending on the type of event: the National Environmental Emergency Centre (NEEC), regional Storm Prediction Centres (SPCs), and Warning Preparedness Meteorologists (WPMs).

The main operational atmospheric transport and dispersion model employed by EERS is called MLDP (Modèle Lagrangien de Dispersion de Particules: D'Amours et al., 2015). EERS provides high-resolution smoke forecasts for tactical purposes and planning decisions (e.g., installing a command post, establishing a security area) and evacuation. For on-demand requests, EERS runs MLDP driven by CCMEP's high-resolution meteorological forecasts from the HRDPS (High Resolution Deterministic Prediction System), a NWP model run on a 2.5-km horizontal grid mesh for each specified hotspot location. In addition, for long-lasting wildfire events EERS can easily set up and install automatic simulations of MLDP on a high-resolution short scale domain for which MLDP also uses HRDPS meteorological forecast data. In that case, near-real-time hotspots detected by satellite imagery and obtained from the Canadian Forest Service's CWFIS are incorporated into the dispersion model together with their associated emissions, thus enabling MLDP to forecast $PM_{2.5}$ concentrations (µg/m³) at ground level. These automatic simulations are updated four times a day. More details can be found at http://eer.cmc.ec.gc.ca/mandats/fire/AutoSim/index_EN.html (protected web page, username and password available upon request).

Conclusion

FireWork, ECCC's new AQ forecast system with near-real-time wildfire emissions has been under development since 2011, and has been run twice daily by the Canadian Centre for Meteorological and Environmental Prediction since 2013. Since 2014, 48-hour FireWork forecasts have also been available to external users through different Internet channels.

From an operational ECCC AQ forecasting perspective, FireWork has been shown to be a very useful tool for forecasting wildfire impacts on AQ.

Going forward, in order to obtain more accurate AQ forecasts that take into account NRT biomass burning emissions, further improvements are planned to a number of FireWork system components, including the estimation of the magnitude and temporal behavior of wildfire emissions, the smoke plume-rise algorithm, and in-plume chemistry. In the meantime, ECCC AQ forecasters and other users of daily AQ predictions can benefit from FireWork forecasts. Furthermore, ECCC is working on enhancing exchanges with external users and partners. This will allow better understanding of clients' needs and improve current and future FireWork products.

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Fire Behaviour Observations from a Significant Mountain Wildfire in West Central Alberta

by Kelsy Gibos

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Introduction

While multiple large wildfires burned elsewhere in dry 2015 spring conditions in the boreal forest across Alberta, a rare lightning strike ignited a wildfire in a remote mountain park in western Alberta. The wildfire made a 12 kilometre run in under four hours that blackened forest indiscriminately from treeline to treeline and added 5,500 hectares to the total area. In three days, it burned over 12,000 hectares of montane forest, challenging traditional suppression tactics with intense fire behaviour and steep, inaccessible terrain.

Fire Chronology

The Rockslide Creek Wildfire (EWF-054-2015) was ignited by lightning in Willmore Wilderness Park in the remote northwest corner of the Edson Forest Area on June 4, 2015. Smoke from the fire was easily visible from the town of Grande Cache 50 kilometres northeast of the fire location. Willmore is fly-in only; no motorized vehicles or equipment are allowed in the park and most recreational users travel by horseback.

Fire danger ratings were into the Very High and Extreme categories for much of the province by the beginning of June following a month of above average temperatures and below average rainfalls related to El Niño. On June 4, 2015, thunderstorms developed around the high country in the western portion of the Edson Forest Area and likely ignited EWF-054-15 (N 53.485417, W-119.225817). At the time of the lightning strike, surface conditions were not favorable for fire spread (light rainfall during the storms). However, over the next few days a dry airmass moved into the central Rockies and began to dry out the forest floor fuels. After a number of days of drying, the fire started to smoke and was detected by a fire lookout tower on June 8, 2015.

The wildfire was reported at 1622 hrs by Simonette Lookout as a light column, medium gray and drifting high. A helitack crew was dispatched to assess the wildfire and their report indicated that the fire was crowning in C-2 (black spruce) fuels and moving at about 15 m/min on a westerly wind (20 km/h) in mild conditions (18°C and 33% relative humidity) and was approximately 10 hectares in size. Photos taken by responding resources indicate a fully developed crown fire moving across the breadth of the Smoky River Valley (approximately 4.5 kilometres wide) (Figure 1). The wildfire remained active into the evening with torching and intermittent crown fire observed through to 2100 hrs even in the shade of the western ridgeline.

On June 9 the wildfire was mapped in the morning at 840 hectares and a Type 2 Incident Management Team (IMT) was organized at the Grande Cache Airtanker Base. The main objective was to limit wildfire spread to the north while supporting hotspotting at the south end along the Jasper National Park boundary. The wildfire was active during the burning period with a few small runs in the afternoon up the west-facing slope of the Smoky River drainage. Helicopters with buckets were used to slow areas of flanking fire spread.

On June 10, moderate southerly winds pushed the wildfire northwards 6 kilometres. The wildfire was not making upslope runs but instead moved northward up the breadth of the valley. Crossover conditions occurred before noon and low relative humidity persisted well into the evening with active crown fire observed through to 2100 hrs. The wildfire began to transition from ground to crown around 1300 hrs, with full crown fire runs starting by 1400 hrs.

On June 11 strong southerly winds early in the day pushed the wildfire further to the north. Winds were observed to be south/southwest 30 km/h in the valley bottom, 60 km/h mid-slope and 80 km/h at the ridgeline. Gusts in the valley bottom were estimated to be around 70 km/h. The wildfire eventually spotted across Hardscrabble Creek and began to spread uphill towards Kvass Creek. The wildfire moved an additional 12 km northwards gaining an additional ~5500 hectares in less than 3 hours (Figure 2). The wildfire's northward momentum was slowed by a combination of a change in fuel type (to younger forest) and the diurnal drop in weather conditions.

On June 12 fire behaviour moderated related to cooler temperatures and climbing relative humidity. The main valley wind switched 180 degrees coming from the north, pushing the fire back into itself. The fire received approximately 11 mm of rain at its southern end on June 13 with some of it falling as snow at higher elevations. As the fire weather eased, ground personnel began to secure perimeter where possible; much of it had already self-extinguished. Direct action was used along the north and south perimeter with bucket support in targeted locations. Due to the remote location and sensitive ecosystems of this wildfire, traditional heavy equipment (dozers, excavators, etc.) were not used. Medium and heavy aircraft were used to cool hotspots

Figure 1. Initial photos of EWF-054-15 on June 8, 2015. Photo above was taken at 1724 hrs. Lower photo was taken at 1740 hrs. (Photos: M. Freedman).

identified with handheld infrared imagery. Areas that were difficult to access (i.e. the eastern flank along the ridge top) were left to self-extinguish. The wildfire was declared 'being held' on June 17 with a final size of 12,052 hectares and estimated perimeter of 80 kilometres. It was deemed 'under control' on June 23 and 'extinguished' on March 14, 2016.

Fire Environment - Topography

The main runs of the Rockslide Creek Wildfire pushed up the north-south aligned Smoky River Valley. Several valleys run perpendicular to the Smoky including one to Azure Lake and Hardscrabble Creek to the east, Twintree Creek to the south and Short Creek, Desolation Creek and No Luck Creek to the west (Figure 3). Short Creek flows from the Resthaven Icefield and into the southern reach of the fire extent. Elevations range from 1400 m in the valley bottom to 2000 m at the top of the tree-line. The wildfire burned mostly east and west aspects from valley bottom to rock but did take some smaller runs up the south-facing slopes of the Azure Lake valley and the edge of Hardscrabble heading towards Kvass Creek.

Wind channeling and valley flow influenced the rate and pattern of fire spread. A westerly wind at Grande Cache tended to become southerly in the Smoky River valley and was substantially stronger than the ambient flow. Wind speed noticeably increased from valley bottom to ridgetop. Cool air drainage (katabatic) from the Resthaven Icefield provided an additional uphill push and valley flow likely prevented spread of wildfire into the Hardscrabble drainage by pushing fire upslope rather than up valley. Although winds with a westerly component tended to channel north in the main valley, they did push fire towards Azure Lake.

Fire Environment Fuels

Like most of the Canadian Rockies, Willmore is located in a lightning strike shadow (Wierzchowski et al. 2002); however the vegetation pattern has been heavily driven by both

Figure 2. EWF-054 looking east (above) on June 11 at 1440 hrs. The photo below is looking south at the head of the fire as it moves towards Hardscrabble creek (Photos: M. Freedman).

lightning-caused and human-caused fire in the recent past. The majority of the park is located in the Rocky Mountain Natural Region, providing representation of the montane, sub-alpine, alpine subregions. There are also components of the Foothills Natural Region (upper foothills subregion) in the Park at elevations below 1500 m. These forest ecosystems map out into a mosaic of Canadian Forest Fire Behaviour Prediction System (Taylor et al. 1997) designated fuel types including C-2 (boreal spruce), C-3 (mature jack or lodgepole pine) and C-4 (immature jack or lodgepole pine). The majority of area burned was made up of C-3, C-4 and C-2 fuels in the form of

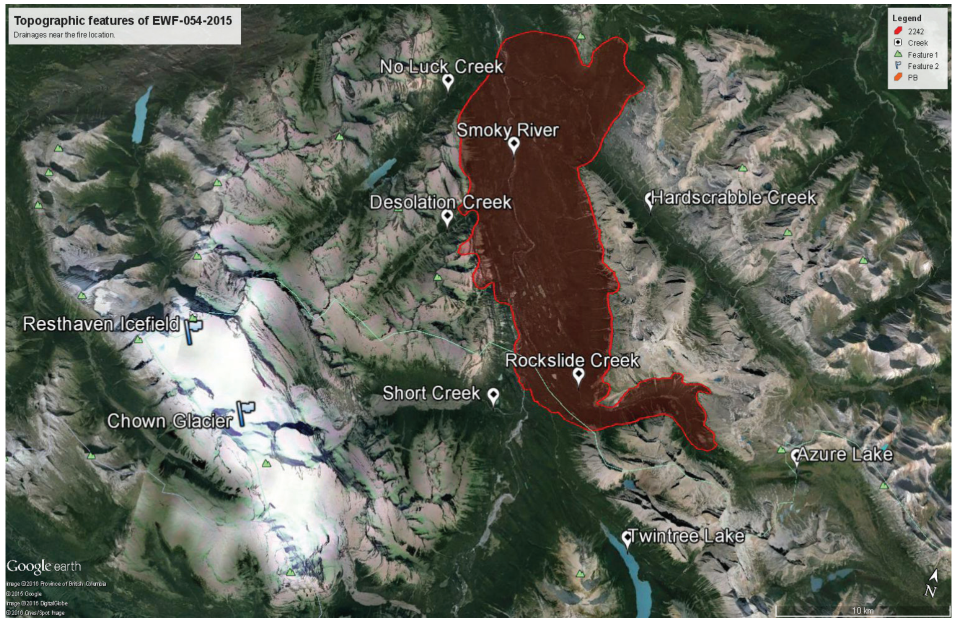

Figure 3. Main valleys and drainages near the Rockslide Creek wildfire.

Figure 4. Fuel complex at the north-end of the wildfire. Note the spruce ladder fuels and the deep feathermoss forest floor. (Photos: K.Gibos)

Engelmann spruce. The forest floor underneath the C-2 fuel type was made up of feathermoss approximately 15 cm deep. The spruce component had significant ladder fuels which were mostly defoliated (Figure 4). The wildfire area was estimated to be snow free about 2 weeks prior to ignition. The soil beneath the feathermoss was observed to be frozen. Examination of bud flush suggests that most of the mid to high elevation fuels were still in the 'spring dip'.

Fire Environment - Weather

The nearest weather station was E5 at Grande Cache more than 50 km northeast of the fire location at the Grande Cache Air Tanker Base. The E5 station (N 53.9165, W -118.8666 at 1250 m) was accurate for assessing temperature and relative humidity at the wildfire. This station is affected by the local topography which tends to funnel wind from the northwest and southwest to more westerly, so wind direction and strength data were unreliable. E5 is a standard permanent Alberta Remote Automatic Weather Station (RAWS) that reports 10 metre, 10 minute average open wind speed, wind direction, temperature, relative humidity, precipitation and dew point.

The local relative humidity (RH) at the wildfire was often observed to be lower than what was forecasted. Two plastic rain gauges were installed at the north and south ends of the fire. On-site weather observations are limited, as the Fire Behaviour Analysts provided support for this fire remotely. A portable RAWS was not available until June 18 due to the high wildfire load across the province.

Antecedent weather conditions were hot and dry related to a long lingering high pressure system. Given that it had only recently become snow free in many parts of the park, Willmore had fairly moist surface and sub-surface fuel conditions at the end of May (Fine Fuel Moisture Code of 65, Duff Moisture Code of 17, Drought Code of 90 on May 31, 2015 at E5- see Footnote 4 for definitions). In early June, the high moved off and allowed small disturbances to pass through including a string of days with thunderstorm activity in the eastern slopes. On June 4 a series of isolated cells passed through the park bringing short bursts of light rain and lightning. Surface fuel conditions were not particularly susceptible to ignition when the storm passed. However on June 7 a suspected dry slot developed over the western edge of the central boreal (Grande Cache, Kakwa, Jasper National Park) bringing clear skies and low relative humidity. Overnight RH did not exceed 60% for the next two days, giving little moisture recovery to the fine fuels. The Fine Fuel Moisture Code (FFMC) climbed quickly, reaching 92 by June 7 at E5.

The day the wildfire was detected (June 8) the relative humidity dropped to a low of 22% in Grande Cache but the maximum temperature (19.5°C) was not enough to reach crossover. Dewpoints across the next few days remained critically low in the dry slot (-1 to -6 °C) bringing crossover conditions to the fire area. On June 9 crossover conditions persisted for 7 hours, beginning at 1300 hrs MDT, with a minimum RH of 11%. On June 10 crossover conditions persisted for 7 hours, beginning at 1100 hrs MDT; on this day, the RH remained below 30% for 11 hours- finally recovering to 50% by midnight. The lowest RH occurred on June 9 at 1900 hrs at 11%.

Winds remained strong (~20 km/h) and westerly throughout the active spread days and were particularly strong on June 11 with gusts of 54 km/h recorded at the 1300 hr reading. Winds on June 11 were stirred up by the passage of a cold front that made its way in central Alberta by midday. The cold front was slowed by a cold low in southern Alberta, giving strong sustained winds for most of the day on June 11.

On June 12 an upper low with associated cold front moved into the province, with the main surface low situated over Calgary. It brought cold air which became snow at higher elevations in the Willmore and a downtrend for most of the province on June 13. Rain gauges at the south end of the fire captured 11.5 mm of rain by the end of the day on June 13 Noon (1300 hrs MDT) standard weather observations at E5 station are presented in Table 1.

Fire Behaviour

During the large run on June 10, the Incident Commander (IC) observed Head Fire Intensity (HFI) Class 5/6

DATE	DRY BULB TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	WIND SPEED (KM/H)	WIND GUST (KM/H)	WIND DIRECTION	DEWPOINT (°C)	FFMC	DMC	DC	ISI	BUI	DSR	FWI
6/7/2015 12:00:00	19.1	31	32		W	2	92	37	136	27	44	19	41
6/8/2015 12:00:00	19.1	25	35	52	W	-1	92	41	143	33	48	26	49
6/9/2015 12:00:00	19.3	21	10	27	NW	-3	93	45	149	11	51	7	24
6/10/2015 12:00:00	20.7	15	21		W	-6	95	50	157	23	56	20	42
6/11/2015 12:00:00	17.8	26	36	54	W	-1	93	54	163	43	59	41	62
6/12/2015 12:00:00	8.8	48	26	45	SW	-1	89	55	168	14	61	12	31
6/13/2015 12:00:00	7.1	100	14		W	7.1	14	23	130	0	32	0	0

Table 1. Fire Weather Index values and weather observations for e5 station for 7 to 13th June 2015. Very high (red) and extreme (purple) values are highlighted in the table.

at the head of the fire and HFI Class 3 at the flanks. On June 10, the wildfire moved about 3.3 km in 1.5 hours which is an average rate of spread of 35-40 m/m. Continuous crown fire filled the valley along the river and the fire tended to spread up the north/ south valley rather than upslope to the east or west. Transition from surface fire began around 1300 hrs, with candling and more organized torching occurring between 1400 and 1500 hrs. The fire continued to crown late into the evening even in the shadow of the ridgeline.

On June 11 helicopters with buckets worked to cool the wildfire in the morning but the fire began to transition from smouldering to flaming just before noon. Fire began to make organized crown fire runs north up the valley. Intensity was estimated to be HFI Class 6 in all fuel types and the fire moved approximately 12 km in 4 hours giving an average rate of spread of 50 m/min. Short-range spotting was reported ahead of the main front (Figure 5).

In most places, canopy consumption was fairly continuous across the valley with 90-100% crown fraction burned (Figure 6). Some areas only surface burned related to either local moisture conditions (mountain spring, lake, swamp) or to transition zones (smouldering to flaming, end of burning period). Fire burned to the treeline at the rock and during the major runs it was indiscriminate to fuel type. The wildfire travelled mainly in the surface fuels (feathermoss) as the deeper organic layers were still frozen in most parts of the valley. Depth of burn was shallow in the locations that the author visited but ground

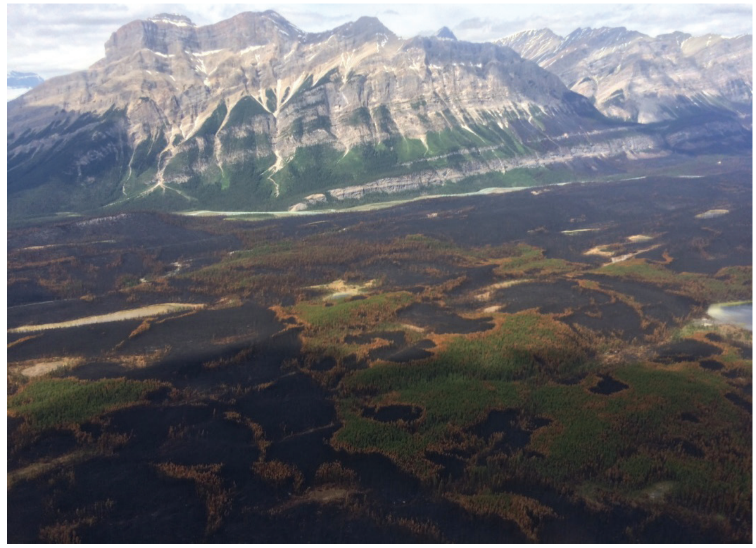

Figure 5. Evidence of short range spotting on Rockslide Creek wildfire looking west perpendicular to the Smoky river (Photo: K.Gibos).

Figure 6. Canopy and Surface Fuel consumption on the Rockslide Creek wildfire (Photos: K.Gibos)

suppression crews suggested there were areas where fire did burn deeper into the fuel bed around tree boles.

Using the Red Book (Field Guide to the Canadian Fire Behaviour Prediction System), the closest weather station (E5) gives reasonable estimates of rate of spread (Table 2). On June 10, observations indicated average spread rates during peak burning of 35-40 m/min and the Red Book estimates of 32-38 m/min (no slope). On June 11, observations indicated average rates of spread of 45-50 m/min and the Red Book estimates of around 60-63 m/min. Rates of spread (ROS) in both the C-2 and C-3 fuel types are similar for these high ISI values (23 on June 10 and 43 on June 11). The fire ran south to north up the main valley with little change in slope, however there were definitely runs up to the treeline driven by slope. If a 20% slope perpendicular to the main valley is accounted for on June 10: in the C-2 fuel type the adjusted rate of spread is 22 m/min; and in the C-3 fuel type the adjusted changes very little to 31 m/min. Observations on the ground suggest that the wind speed mid-slope

	FUEL TYPE	ROS (M/MIN)	HFI (KW/M)	HFI CLASS	HEAD FIRE TYPE	FLANK FIRE TYPE
10 June 2015	C-2	38	36,100	6	Crown	Intermittent Crown
	C-3	32	26,500	6	Crown	Surface
11 June 2015	C-2	60	58,800	6	Crown	Intermittent Crown
	C-3	63	53,900	6	Crown	Surface

Table 2. Noon STANDARD (13:00 MDT) FBP outputs for boreal spruce (C-2) and lodgepole pine (C-3) fuel types for the Rockslide wildfire on 10-11th June 2015 (no slope) using weather data from E5 station and outputs from the Red Book (Taylor et al. 1997).

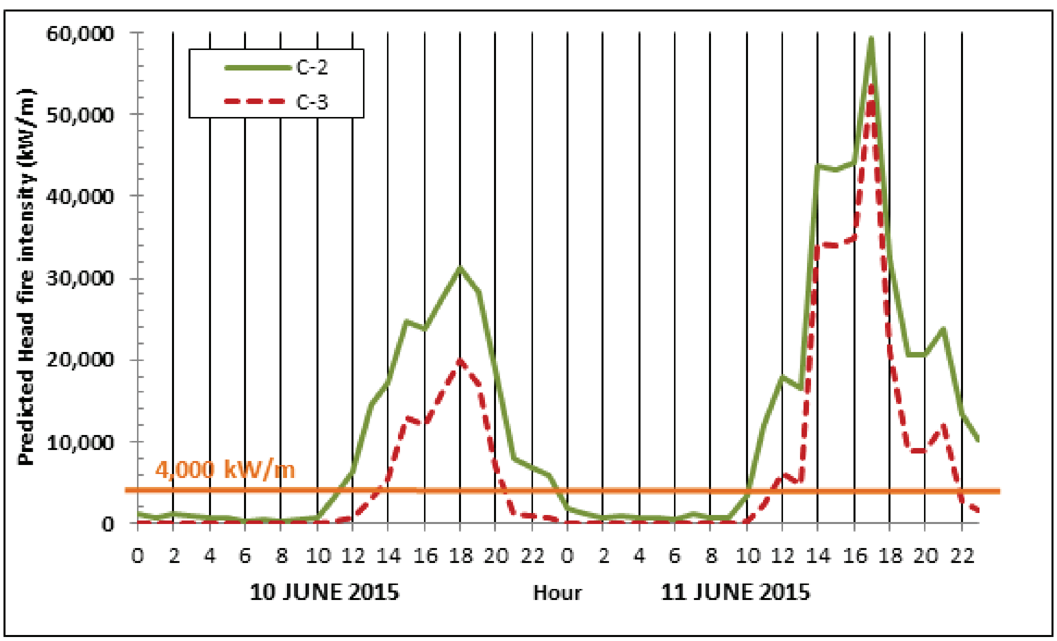

Figure 7. Headfire Intensity curves for C-2 and C-3 fuel types on 10 and 11 June 2015 using hourly weather data from E5. The diurnal (Lawson) method was used to adjust hourly FFMC.

in the valley was much stronger on June 11 than what was reported at E5. If the observation of 60 km/h is used, the ROS on June 11 in the C-2 fuel types increases to 80 m/min and in the C-3 fuel types increases to 90 m/min. Perimeter growth rate ranged from 70-100 m/min on June 10 to 130-140 m/min on June 11.

Diurnal headfire intensity curves were created for C-2 and C-3 fuel types using REDApp and hourly weather data from E5 (Figure 7). The curves indicate that wildfire was expected to be beyond resources (> 10,000 kW/m) in C-2 by noon and remain at HFI Class 6 through to 2100 hrs. Fire in C-3 was expected to exceed HFI Class 6 from 1400 hrs through to 2000 hrs. Fire behaviour was expected to beyond direct attack (> 4,000 kW/m) for more than 12 hours on both days. These estimates match the general fire behaviour observations from the field.

Discussion

The FBP system was fairly accurate at predicting rates of spread and head fire intensities for this wildfire based on observations from the fire line. It was difficult to anticipate the blow

Text Box 1: FIRE BEHAVIOUR NOTES FROM THE ROCKSLIDE CREEK FIRE

1. **Effect of frozen ground:** The Smoky Valley had only recently become snow free, leaving much of the underlying organic layers frozen solid. Without moisture transport from below, the feathermoss responded very quickly to dropping RH, increased solar radiation (longer days) and wind speed. Frozen ground limits the effect of BUI on spread leaving potential for an ISI driven event.

2. **Spring dip:** Buds on the coniferous trees in the fire area were beginning to burst, suggesting that the foliar moisture content was likely lower than the 97% assumed in the FBP System. Although there is no current field study or empirical analysis that has examined the effect of the moisture content of live fuels on the propagation of high intensity fires (Alexander and Cruz 2013), an effect has been observed at both the field and laboratory scale. Recent research suggests that it is the seasonal change in foliar chemistry rather than the moisture content variation that causes an Increase in flammability in the spring (Jolly et al. 2014). The ease of transition from ground to crown fire may have been influenced by the seasonal state of the conifer needles on the Rockslide Creek Fire.

3. **The dry slot**: A band of dry air that is often associated with an approaching low pressure system may have been responsible for rapid surface drying and increased gusty winds on this fire. Although there are limited documented case studies specifically relating to the dry slot, there are a number of anecdotal observations. Some major examples of suspected dry slots include the Mann Gulch Fire (1949) and the Mack Lake Fire (1980) (Schoeffler 2013) and major fires across Australia in 2003 that resulted in the deaths of 4 people and a loss of over 500 structures (Mills 2005). In all cases the dry slot pattern was responsible for decreased dew points and RH resulting in abrupt near-surface drying, decreased fuel moisture and increased gusty winds on the blow up days.

4. **Mountain winds:** Mountain wind dynamics are difficult to forecast and are complicated by multiple factors including: shape of topography, glacial winds, small scale channeling, subsidence and up-valley flow. Wind direction is an important component of fire growth modelling and determining subtleties in changes in direction and strength in a complex mountain environment is challenging. Thinking about the direction of observed fire spread should help model appropriate wind fields, but anticipating changes in direction as the fire moves up valley requires solid field observations.

5. **Spring conditions:** Frozen ground and changes in foliar chemistry are seasonal occurrences. Arctic air masses can make their way into Alberta in the spring presenting issues of subsidence where cold, dry air sinks from height. In the lowering process, the subsiding air mass has little opportunity to mix with other moist air until it comes to a relatively low level. Severe subsidence tends to occur on the lee side (think Alberta side of the Rockies!) of the mountain range (Krumm 1955). Subsiding air combined with an evening downslope wind in the mountains can create severe fire weather conditions. The combination of dry surface fuels, stressed and decadent vegetation and potential for wind events related to high pressure systems (subsidence) or approaching low pressure systems (dry slots) in the spring gives rise to an alignment of conditions for potential development of large fires.

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up of this wildfire; there were several key conditions aligning including dry air, low relative humidity, desiccated surface fuel, 'spring dip' and a wind event all of which were obvious in hindsight, but difficult to see during the incident given the provincial wildfire load and remoteness of Willmore Wilderness Park (Text Box 1).

The 2015 Rockslide Creek Wildfire occurred during a period when mountain wildfires were normally at a minimum and the standing boreal forest wildfire load was very high. A number of fire behaviour planets were quietly aligning but local situational awareness of the fire environment was limited due to the park's remoteness and the lack of expectation due to an infrequent fire regime. The Rockslide Creek Wildfire was a reminder to closely monitor weather conditions in areas that may not be frequented by boots on the ground and a lesson about specific triggers for large fire potential in the mountains.

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