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FIREWORK: ENVIRONMENT CANADA'S NORTH AMERICAN AIR QUALITY FORECAST SYSTEM WITH NEAR-REAL-TIME WILDFIRE EMISSIONS

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1. INTRODUCTION

Biomass burning, either prescribed, natural, or accidental, can generate significant amount of pollutants and pollutant precursors that can affect air quality (AQ) over a various range of scales, from local to inter-continental (Bertschi and Jaffe, 2005; Cottle et al., 2014).

An experimental North American AQ forecast system with near-real-time wildfire emissions called FireWork was developed by Environment Canada (EC) to provide forecasts of wildfire smoke impacts. This system is identical to EC's operational regional AQ forecast system except for the inclusion of wildfire emissions. While 48-hour AQ forecasts issued by FireWork have been available to EC operational forecasters since 2013, some FireWork products have also been available to external users since 2014. The system has been run twice daily for the wildfire season from around June to November for several years by the operational division of EC's Canadian Centre for Meteorological and Environmental Prediction.

Near-real-time satellite-based information about active wildfires in both Canada and the U.S. is provided to FireWork via the Canadian Wildland Fire Information System (CWFIS), which is operated by Natural Resources Canada (NRCan). These "hotspot" data are then used with other geospatial information to estimate emissions from each fire. The emissions for each fire are then injected into elevated model layers in FireWork based on plume-rise calculations, followed by transport and chemistry calculations.

In this document, a brief introduction to FireWork system and performance analyses of $PM_{2.5}$ forecasts for 2014 and 2015 seasons are presented. We also describe ongoing and future work planned for the FireWork system.

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2. FIREWORK SYSTEM OVERVIEW

2.1 *Development Platform*

The Regional Air Quality Deterministic Prediction System (RAQDPS), EC's regional AQ forecast system, has been run operationally by Environment Canada since the summer of 2001. Since 2009, the heart of the RAQDPS has been a limited-area configuration of the GEM-MACH model, which consists of an on-line chemical transport model embedded within the Global Environmental Multi-scale model (GEM), EC's multi-scale operational weather forecast model (Coté et al., 1998a,b; Charron et al., 2012; Moran et al., 2009, 2012, 2013, 2015; Im et al., 2015). The RAQDPS is run twice daily to produce 48-hour forecasts of hourly surface concentration fields of ozone (O_3), nitrogen dioxide (NO_2), particulate matter with aerodynamic diameter smaller than 2.5 µm ($PM_{2.5}$), and other chemical species on a North American grid. Currently, the RAQDPS grid has 10-km horizontal spacing and 80 vertical levels extending up to 0.1 hPa. RAQDPS forecasts are used as guidance by operational AQ forecasters at EC and elsewhere.

2.2 *Development Chronology*

The FireWork system was developped by EC's Air Quality Application and Modelling Section (AQMAS) beginning in 2011 (Chen et al., 2011, 2013; Pavlovic et al., 2014, 2015). In 2011, the emissions generation and modelling method were established and fire information from Canada and the U.S. was processed for historical cases. In 2012 several case studies were performed and the new system was named FireWork. In 2013, the model was run for the entire summertime period and forecasts were made available to EC operational AQ forecasters. In 2014 and 2015, FireWork was run by EC Operations in an official experimental mode and forecasts were made available to external users.

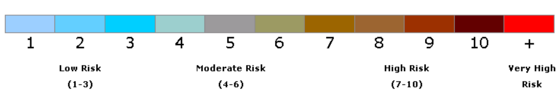
2.3 *Forecast Products*

The fact that the only difference between FireWork and the operational RAQDPS is the inclusion of wildfire emissions in FireWork means that any differences in concentration forecasts between the two model versions are due solely to wildfire emissions. Surface $PM_{2.5}$ concentration difference plots thus provide a straightforward way to determine the location, strength, and arrival and departure time of smoke plumes from individual wildfires or groups of wildfires. Closely related products that can be used by forecasters include vertically-integrated $PM_{2.5}$ concentration difference fields as well as time loops and time integrations of hourly concentration difference fields.

The provision of warnings about expected poor air quality and associated health impacts is an important aspect of operational AQ forecasts. Such warnings are communicated by EC to the Canadian population in terms of a multi-pollutant Air Quality Health Index (AQHI), which was developed through epidemiological studies (Stieb et al., 2008). This hourly index expresses the total health risk of a mixture of air pollutants and has a range from 0-10+. It is calculated as a weighted sum of local O_3, $PM_{2.5}$, and NO_2 surface concentrations using the following equation:

$$\mathbf{AQHI} = (10/10.4)*100*[(\exp(0.000871*\mathbf{NO_2})-1) + (\exp(0.000537*\mathbf{O_3})-1) + (\exp(0.000487*\mathbf{PM_{2.5}})-1)]$$

Higher AQHI values indicate greater health risks as shown by the following graphic:



An alternate AQHI based on FireWork forecasts instead of RAQDPS forecasts was calculated for all Canadian AQHI sites. These alternate AQHI values thus include the contribution of smoke from wildfires, which is missing from the RAQDPS forecasts.

2.4 *Wildfire Emissions Estimation*

As part of the development of FireWork, a wildfire emissions processing system had to be built to estimate near-real-time emissions from wildfires and large prescribed burns and then format them for input into the model. The resulting FireWork dataflow and emission generation procedure is presented on Fig. 1.

Since the FireWork forecast domain covers Canada and most of the continental U.S., including Alaska, fire location information is needed for both of these very large countries. The CWFIS uses observations from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite-based detection systems to detect active wildland fires (Anderson et al., 2009). Forecasted meteorology from Environment Canada's GEM model is then used to determine weather conditions at fire locations, which allows fuel consumption to be estimated (Anderson et al., 2009; Van Wagner 1987).

The BlueSky Fire Emission Production Simulator (FEPS) module is then used to calculate daily total emissions for each fire "hotspot" (Larkin et al., 2009). Finally, the SMOKE emissions processing software (CEP, 2012) is used to convert daily total wildfire emissions into hourly values and to convert bulk VOC, NO_x, and $PM_{2.5}$ and PM_{10} emissions into explicit modelled species. SMOKE default wildfire speciation profiles provided by the U.S. EPA are applied for chemical speciation. These hourly processed wildfire emissions are merged with anthropogenic point-source emissions and then provided to FireWork as a combined daily point-source emissions file. These emissions processing procedure allows FireWork to use the same "infrastructure" as the RAQDPS with only one difference: near-real-time biomass burning emissions.

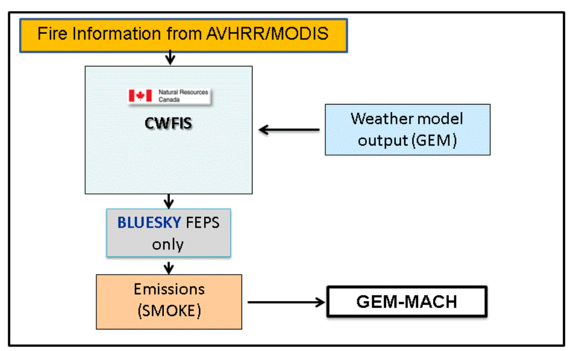


Fig.1. FireWork framework and dataflow.

3. FIREWORK PERFORMANCE ANALYSIS

The summers of both 2014 and 2015 saw intense wildfires raging in northwestern Canada. In summer 2014, the Northwest Territories (NWT), especially the Yellowknife region, experienced many large fires in June and July. Smoke from these wildfires reached eastern Canada and the eastern U.S. and was even observed as far away as Portugal (Davignon et al., 2014). Figure 2a shows the average summertime (June-August) impact of all wildfires during this period on surface $PM_{2.5}$ concentrations as forecasted by FireWork. The average contribution was above 30 µg m^{-3} in many regions in Canada (NWT, Alberta, and British Columbia) and the western U.S. (California, Oregon, Washington, and Idaho).

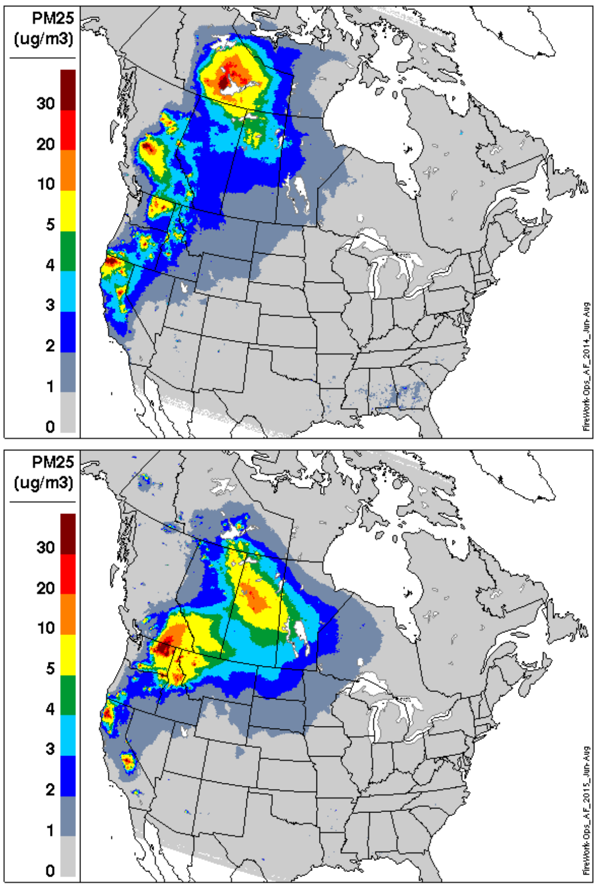


Fig. 2. Forecasted summertime (June-August) 2014 (top) and 2015 (bottom) wildfire emissions contribution to average surface $PM_{2.5}$ concentrations (µg/m^3).

To evaluate model performance, hourly FireWork forecasts were first extracted at the locations of observation sites (Fig. 3). These forecast values were then paired with hourly observed data available via EC's VAQUM (Verification of Air QUality Models) system, a geospatial database tool that enables model evaluation to be performed using Canadian and U.S. hourly measurements (Gilbert et al., 2014).

For the summer of 2014, FireWork objective scores for hourly $PM_{2.5}$ are significantly better than corresponding scores for the RAQDPS (Table 1). For western Canada, the region most affected by wildfires (see Figs. 2a and 3), the correlation coefficient R for FireWork was 0.40 vs. only 0.10 for the RAQDPS. However, $PM_{2.5}$ was underpredicted on average in western Canada by both model versions: -1.0 µg m^{-3} and -4.3 µg m^{-3} for FireWork and the RAQDPS, respectively. Time series of observed and forecasted concentrations for National Air Pollution Surveillance (NAPS) network station 91801 in northern Alberta, one of the stations most affected by wildfire smoke during this period, are presented in Fig. 4. We can see from this figure that FireWork has performed well in forecasting the periods when the station will be affected by wildfire smoke, although peak values are under-predicted.

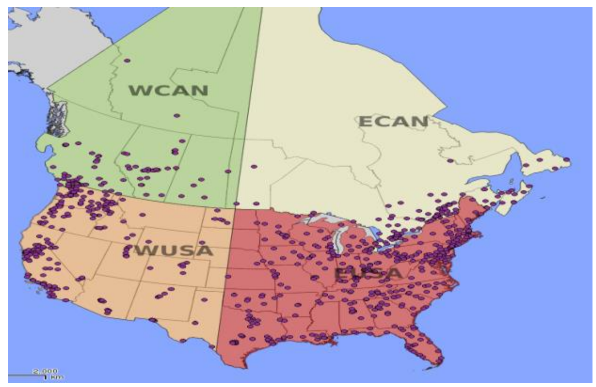


Fig. 3. $PM_{2.5}$ surface stations with available observations for summer of 2015 (June-September). The four regions shown with different colours are used for the statistical analysis presented in this document.

Table 1. Hourly performance statistics for $PM_{2.5}$ for summer 2014 (10 June – 17 September) for RAQDPS and FireWork 48-hour forecasts. The three statistics considered were mean bias (MB), Pearson correlation coefficient (R), and unbiased root mean square error (URMSE). Yellow-coloured boxes indicate a better forecast with FireWork, blue boxes indicate a better forecast with the RAQDPS, and grey boxes indicate no statistically significant difference between the two model versions. The statistical significance of the differences in each statistic was determined by a bootstrap calculation for a confidence interval of 95%.

Statistic	**Canada**		**Western Canada**		**Eastern Canada**	
	RAQDPS	FireWork	RAQDPS	FireWork	RAQDPS	FireWork
MB	-1.47	0.25	-4.29	-0.96	0.86	1.24
R	**0.19**	**0.38**	**0.10**	**0.40**	**0.37**	**0.39**
URMSE	11.21	11.21	12.11	12.59	9.82	9.83

In 2015, intense wildfires were already present in parts of northwestern Canada in May, and in June and July they were unusually numerous, strong, and persistent in northern Saskatchewan and Alberta and in parts of the NWT (see Fig. 2b). In fact, during this period FireWork was unable to handle all of the fires that were detected by satellite due to operational time constraints, so that many sources were rejected. This problem was fixed on 20 July 2015, after which FireWork was able to handle up to 28,000 hotspots per day.

Objective scores for the summer of 2015 are presented in Table 2. In western Canada the correlation coefficient R was 0.49 for Firework vs. 0.09 for the RAQDPS, while mean bias (MB) was -2.0 µg m^{-3} and -5.1 µg m^{-3}, respectively. Note that the negative MB for FireWork is partly due to the rejected hotspots that occurred before July 20.

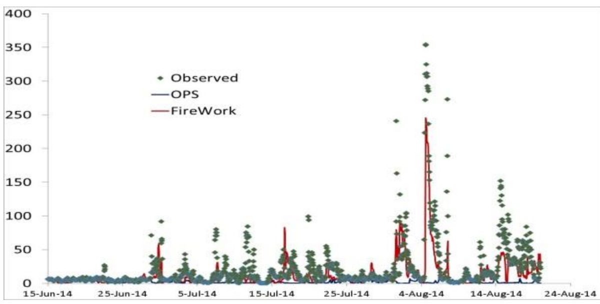


Fig. 4. Time series of forecasted and observed hourly $PM_{2.5}$ surface concentrations at NAPS station 91801 in northern Alberta in summer 2014. FireWork forecasts are shown by the red line; RAQDPS forecasts are shown by the blue line. The observed concentrations are indicated by green points.

Table 2. Same as Table 1 but for summer 2015 (2 June – 2 September).

Statistic	Canada		Western Canada		Eastern Canada	
	RAQDPS	FireWork	RAQDPS	FireWork	RAQDPS	FireWork
MB	-2.38	-0.69	-5.14	-2.02	-0.10	0.40
R	**0.12**	**0.47**	**0.09**	**0.49**	**0.35**	**0.41**
URMSE	14.36	14.25	18.72	18.83	8.71	8.66

Figure 5 shows time series of forecasted and observed $PM_{2.5}$ surface concentration for two Canadian cities, Saskatoon and Calgary, that were heavily affected by smoke from wildfires in summer 2015. FireWork performed well in forecasting the periods when Saskatoon and Calgary were affected, though with under- and over-predicted concentrations in Saskatoon and Calgary, respectively.

For the western U.S., which also experienced many wildfires in summer 2015, we analyzed FireWork performance in the states of Oregon and Idaho. Figure 6 shows time series of forecasted and observed $PM_{2.5}$ surface concentration at two Air Quality System (AQS) stations, one in Oregon and one in Idaho. Again, the periods with heavy smoke impacts are generally well forecast by FireWork, but some overpredictions or underpredictions can be seen.

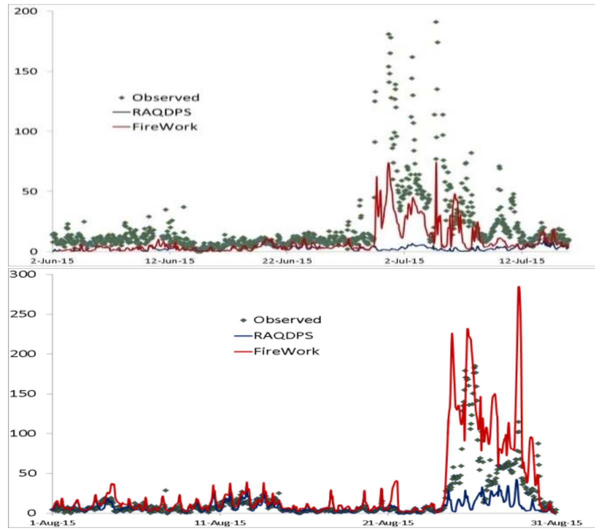


Fig. 5. Same as Fig. 4, but for Saskatoon (top) and Calgary (bottom) in summer 2015. Observations from NAPS station 80211 were used for Saskatoon; for Calgary the observed concentrations are an average of NAPS stations 90228 and 90222.

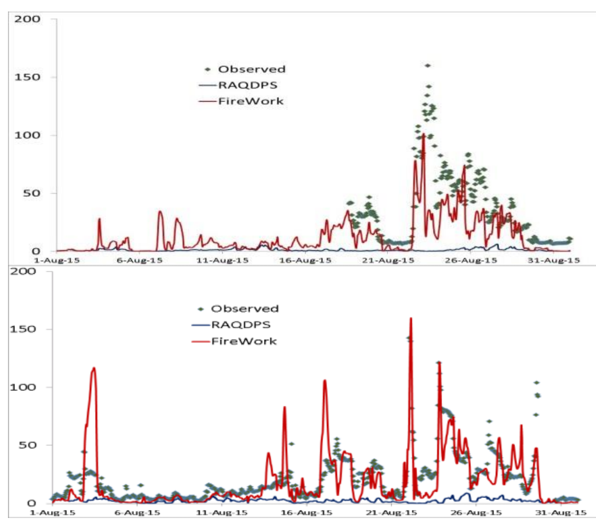


Fig. 6. Same as Fig. 5, but for (top) AQS station 410610120 in Oregon and (bottom) AQS station 530750006 in Washington. Note that for station 410610120, observations are not available for the period 1–14 August 2015.

The right side of Figure 7 shows a satellite image from 29 June 2015 in which an extremely dense "river" of smoke is visible over central Canada and the central U.S. We analyzed the FireWork forecast from the day before, June 28, which was valid on June 29. The position of the forecasted smoke plume for June 29 (left side of Fig. 7) matches the satellite image very well.

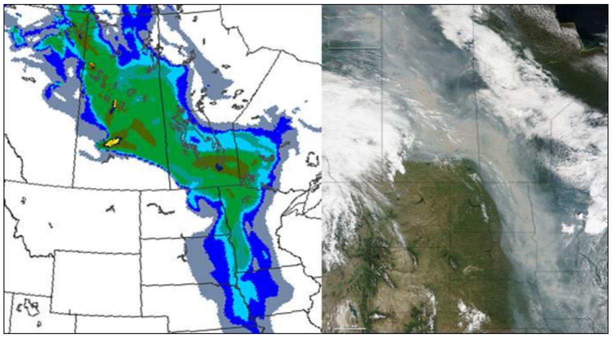


Fig. 7. The forecasted plume position (left) from vertically-integrated $PM_{2.5}$ concentration from the 2015-06-28 12 UTC FireWork run valid at 2015-06-29 12 UTC and (right) a visible-spectrum satellite image taken on 2015-06-29 at 12 UTC (source: NASA Earth Observatory http://earthobservatory.nasa.gov).

The forecasted contribution of wildfires to $PM_{2.5}$ surface concentrations at individual measurement stations in summer 2015 is shown in Fig. 8 (top). This contribution was obtained simply by extracting average FireWork and RAQDPS forecasts for these locations and calculating the difference. Note that the geographic range and the magnitudes of these contributions are consistent with Fig. 2b. For all of the stations affected by smoke from wildfires, the correlation coefficient R is also higher for FireWork in both Canada and the U.S. (Fig. 8 bottom). This result is consistent with the results presented in Tables 1 and 2, where regional R values were also significantly improved with FireWork.

Starting in 2015, FireWork was connected to EC's Regional Deterministic Air Quality Analysis (RDAQA) post-processing package (Robichaud and Ménard, 2014). This package was initially developed for the RAQDPS and produces near-real-time hourly North American surface objective analyses (OA) of a number of observed species, including $PM_{2.5}$ and PM_{10}. The FireWork version, named RDAQA-FW, uses a combination of AQ measurements and gridded FireWork forecast fields. Before connecting RDAQA-FW to the FireWork system, the entire summer 2014 period was first run as a test.

RDAQA-FW was found by operational AQ forecasters to be very useful, as it allowed them to adjust FireWork forecasts when long-range transport was important. Figure 10 shows results for one interesting case on 9 July 2014 when the difference between the FireWork $PM_{2.5}$ forecast and the subsequent RDAQA-FW analysis was large. In July 2014 there were very intense wildfires burning in the NWT, and it took approximately 24 hour for smoke from these fires to be advected to southern Manitoba, Montana, and North Dakota. For this particular case, FireWork underpredicted $PM_{2.5}$ surface concentrations, but operational AQ forecasters were able to adjust the forecast since they knew that further downwind the forecasted $PM_{2.5}$ concentrations would also be underestimated.

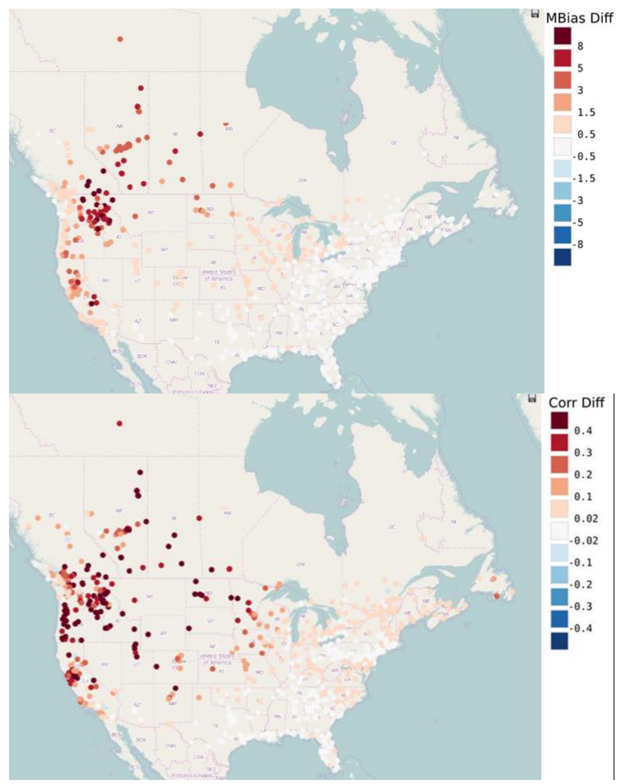


Fig. 8. Average per-station differences in MB (top) and R (bottom) for $PM_{2.5}$ between FireWork and RAQDPS for summer 2015 (2 June – 2 September).

4. SUMMARY AND CONCLUSIONS

The FireWork North American AQ forecast system with near-real-time wildfire emissions has been under development at Environment Canada since 2011, and it has been run experimentally each year since 2013 during the wildfire season.

A performance analysis of FireWork forecasts for both Canada and the U.S. for the summers of 2014 and 2015 showed noticeable improvements in $PM_{2.5}$ forecasts for those regions impacted by wildfires, and FireWork has also demonstrated skill in forecasting long-range smoke transport from wildfires. FireWork performed well in forecasting the periods when a region would be affected by wildfire smoke, including arrival and departure times. However, $PM_{2.5}$ concentrations during these periods may be either underpredicted or overpredicted. These errors in predicted concentration magnitudes may be due to errors in both model inputs and the model itself, including emissions estimates, the plume-rise algorithm, and the meteorological forecasts.

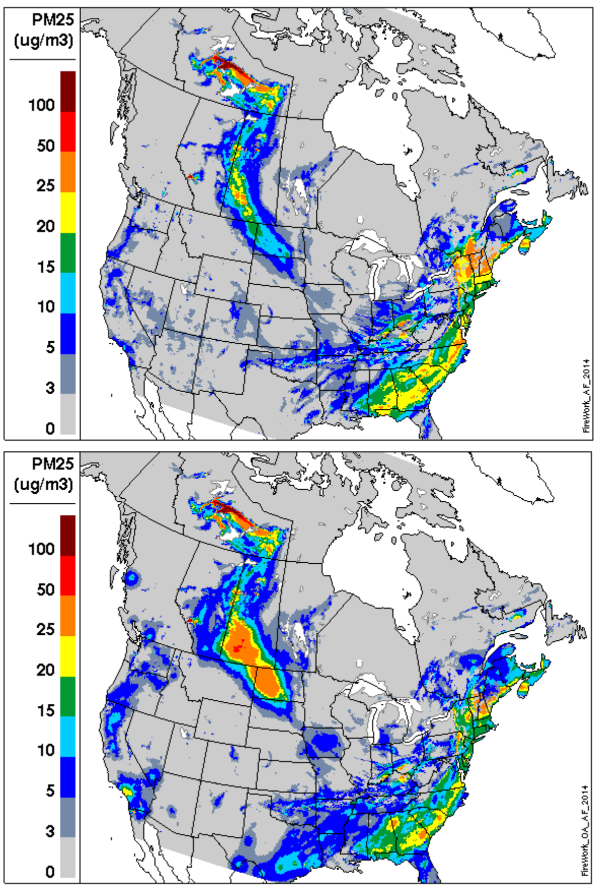


Fig. 9. $PM_{2.5}$ surface concentrations on 9 July 2014 forecasted by FireWork (top) and adjusted by RDAQA-FW (bottom).

5. FUTURE WORK

Going forward, the next release of both the RAQDPS and FireWork will likely include a major update to the model source code. The RAQDPS and FireWork versions to date have been built on version 3 of the GEM numerical weather prediction model. However, a new generation of the GEM model, version 4, has been available for several years and a GEMv4-based version of the RAQDPS source code has been developed and is currently under testing.

We are also working on an improved plume-rise algorithm for wildfire emissions. As well, research on different approaches to estimate wildfire emissions is also underway. We are testing U.S. Forest Service (USFS) emissions for the U.S. as our objective is to use USFS wildfire emissions estimates for the U.S. and CWFIS emissions for Canada.

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